

Diameter as a control knob: Tuning magnetic states and collective dynamics in FeCo nanowire arrays for self-biased microwave devices

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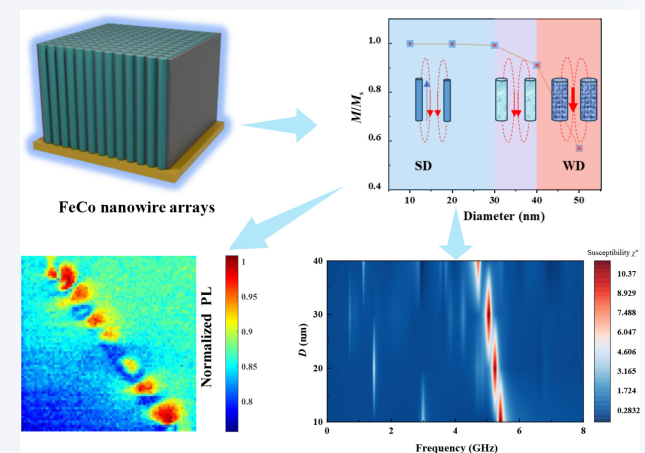
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ABSTRACT: FeCo alloy nanowires exhibit high saturation magnetization and tunable anisotropy, making them attractive for self-biased microwave devices. However, their magnetic performance is limited by magnetostatic interactions and multi-domain states that degrade coercivity and remanence squareness. This work demonstrates that nanowire diameter directly governs this magnetic complexity. Using experiment and micromagnetic simulation on electrodeposited Fe₆₇Co₃₃ nanowire arrays, we revealed a sharp transition from multi-domain to single-domain configurations below 30 nm. This transition was visualized by scanning nitrogen-vacancy magnetometry and Lorentz transmission electron microscopy. First-order reversal curve analysis quantifies a significant reduction in inter-wire magnetostatic coupling with decreasing diameter, indicating improved magnetic uniformity. Dynamic simulations show that larger diameters introduce multi-domain resonance modes and enhance inter-wire coupling, leading to complex collective behavior. Ferromagnetic resonance spectroscopy provides key material parameters, including gyromagnetic ratio, Gilbert damping constant, and saturation magnetization derived from an effective field model. These results establish that precise diameter control below 30 nm optimizes individual nanowire properties while suppressing array-level coupling, resulting in enhanced coercivity and a stable single-domain state. As a demonstration, a Y-junction circulator based on these nanowire arrays shows promising microwave performance. This work offers a materials-oriented roadmap for engineering high-performance self-biased magnetic devices.

KEYWORDS: FeCo nanowires, magnetic anisotropy, first-order reversal curves (FORC), micromagnetic simulations, self-biased circulators

1 Introduction

FeCo alloy nanowires represent a promising material platform for advanced microwave technologies, benefitting from their superior magnetic properties, including high saturation magnetization, permeability, and Curie temperature [1, 2]. Their pronounced



magnetic anisotropy, largely derived from shape anisotropy, renders them particularly suitable for self-biasing device architectures such as compact circulators in phased-array systems [3–5]. Unlike conventional ferrite-based circulators that require external permanent magnets, self-biased circulators exploit the intrinsic magnetic anisotropy and remanence of functional materials, enabling reduced device size and improved system integration. Ferromagnetic nanowire arrays are particularly attractive in this context due to their strong shape anisotropy, tunable collective magnetic response, and controllable dynamic behavior, making them promising candidates for compact high-frequency microwave devices.

A principal challenge in deploying these nanowires is the precise

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fabrication of arrays that simultaneously exhibit high remanence squareness ($SQ = M_r/M_s$, where M_r is remanent magnetization, and M_s is saturation magnetization) and well-defined magnetic anisotropy [6]. These magnetic characteristics arise from a complex interplay of shape anisotropy, magnetostatic interactions between nanowires, and magnetocrystalline anisotropy [7–9]. Substantial research has therefore been directed toward synthesizing and characterizing FeCo nanowires to achieve the tailored properties required for stable operation in applications like self-biased circulators.

Extensive investigations confirm that key magnetic properties of FeCo nanowires, such as coercivity (H_c), saturation magnetization (M_s), and magnetic anisotropy, can be effectively modulated by varying their geometric parameters and chemical composition [10–14]. For instance, Vázquez et al. systematically studied Ni nanowire arrays and found that both coercivity and remanence decrease with increasing diameter-to-spacing ratio due to enhanced magnetostatic interactions [15]. The influence of diameter on the micro-magnetic properties, including the transition of hyperfine fields and magnetic moment orientation, has also been revealed in FeNi nanowire systems [16]. Furthermore, detailed analyses using first-order reversal curve (FORC) have proven powerful in deconvoluting the effects of dipolar interactions and identifying reversal mechanisms, such as the reversal-field memory effect, in complex nanowire arrays [17, 18]. More recently, Palmero et al. demonstrated a stepwise magnetization reversal in diameter-modulated $\text{Fe}_{50}\text{Co}_{50}$ bi-segmented nanowires, highlighting the critical role of geometrical tuning [19].

Among these, nanowire diameter is especially critical, as it fundamentally dictates the magnetic state and reversal mechanism. A well-recognized phenomenon is the transition from a multi-domain (MD) to a single-domain (SD) configuration when the diameter is reduced below a critical threshold [20]. In nanowires with larger diameters, domain wall formation lowers magnetostatic energy, resulting in relatively low coercivity. As the diameter decreases, the energy required to sustain a domain wall eventually exceeds that of the single-domain state. This shift to a coherent magnetization rotation mode markedly enhances both coercivity and remanence [21, 22]. Furthermore, reducing the diameter amplifies the influence of shape anisotropy, which constitutes the dominant contribution to the overall magnetic anisotropy in these systems [23]. A smaller diameter increases the shape anisotropy constant, thereby raising the energy barrier for magnetization reversal and improving thermal stability. At the same time, diameter reduction modifies inter-wire magnetostatic interactions; although the intrinsic properties of individual nanowires may improve, the typically higher packing density achievable with smaller diameters can alter collective array behavior, affecting parameters such as remanence squareness [19, 24]. Consequently, precise diameter control is essential not only for optimizing intrinsic properties like H_c but also for managing the trade-offs between individual nanowire performance and array-level magnetic response.

Despite these advances, a systematic and causally clear understanding of how diameter simultaneously dictates the internal magnetic state, the reversal mechanism, and the inter-wire interactions in dense arrays remains incomplete. Decoupling these intertwined effects is crucial for moving from empirical optimization to rational design of nanowire-based devices. In this work, we address this gap by employing a multiscale

characterization strategy. We combine macroscopic magnetic measurements (vibrating sample magnetometer (VSM) and FORC) with direct nanoscale imaging (Lorentz transmission electron microscopy (LZ-TEM) and scanning nitrogen-vacancy (NV) microscopy (SNVM)) and are further supported by comprehensive micromagnetic simulations spanning both static reversal and dynamic response. This integrated approach allows us to establish a direct and unambiguous link between the geometric parameter of diameter and the resulting magnetic properties. We demonstrate that diameter reduction is not merely a means to enhance individual nanowire coercivity but, more importantly, a potent strategy to suppress collective inter-wire coupling and simplify dynamic response. This provides a key insight for designing arrays that function as intended in practical microwave applications. Our findings therefore provide both fundamental understanding and practical design guidelines for tuning FeCo nanowire arrays towards optimized performance in self-biased circulators and related high-frequency technologies.

2 Experimental

Based on theoretical calculations and prior work, the diameter range of 20–40 nm was selected, as it likely covered the critical size for the transition from single-domain to multi-domain states [21]. The experiment employed commercially available anodic aluminum oxide (AAO) templates from Topmembranes Technology Co., Ltd. as the supporting substrate for the electrochemical growth of nanowires. FeCo nanowire arrays were synthesized using a three-electrode electrochemical deposition system. A double-sided AAO template was employed, with one side coated with an 800 nm Ag layer via magnetron sputtering to serve as the working electrode. A platinum (Pt) electrode was used as the counter electrode, and a saturated calomel electrode (SCE) was utilized as the reference electrode. The electrolyte solution, with a volume of 100 mL, was prepared at room temperature (25 °C) and consisted of 0.06 M $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 0.03 M $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$, 0.1 M $(\text{NH}_4)_2\text{SO}_4$, 0.01 M ascorbic acid ($\text{C}_6\text{H}_8\text{O}_6$), and 0.4 M boric acid (H_3BO_3). The close deposition potentials of iron and cobalt enabled control over the Fe/Co atomic ratio in nanowires by adjusting the molar ratio of iron to cobalt sulfates in the electrolyte. Based on relevant studies, the pH of the electrolyte was maintained between 3.0 and 4.0 to facilitate the co-deposition of cobalt and iron. $\text{C}_6\text{H}_8\text{O}_6$ acted as a reducing agent to prevent the oxidation of Fe^{2+} to Fe^{3+} in the solution. H_3BO_3 was added to stabilize the electrolyte. Electrochemical deposition was carried out at a constant potential of -1.2 V (vs. SCE) to reduce Fe^{2+} and Co^{2+} ions into the AAO template. $\text{Fe}_{67}\text{Co}_{33}$ was deposited using templates with different pore diameters (20, 30, and 40 nm, as seen in Fig. S1 in the Electronic Supplementary Material (ESM)). The schematic diagram of the preparation principle of FeCo nanowires is also shown in Fig. 1.

The deposition of nanowires was performed using an electrochemical workstation (EWS, CH760, China). Magnetic hysteresis loops and FORC measurements were conducted with a VSM (Model 3100, East Changing Technologies). The morphology of the materials was measured by scanning electron microscopy (SEM, CIQTEK DB550), and the distribution of each element was analyzed by energy dispersive X-ray spectroscopy (EDS) mapping. The detailed crystal structure characteristics were examined by high-resolution transmission electron microscopy (HRTEM, FEI Tecnai F20, USA). The magnetic domains of FeCo nanowires were tested

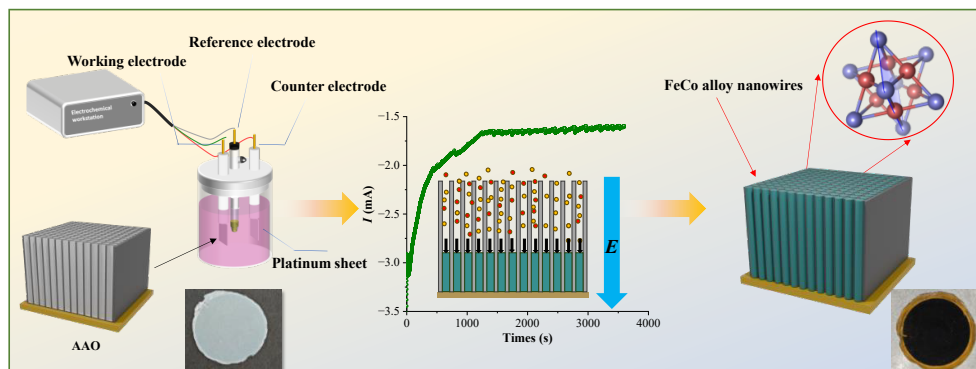


Figure 1 Schematic diagram of the preparation principle of FeCo alloy nanowires. FeCo nanowire arrays were synthesized using a three-electrode electrochemical deposition system. Chronoamperogram recorded during the growth of CoFe composite within the AAO membranes is also given. In the early stages of the electrochemical growth, the establishment of the diffusion layer contributes to the decrease of the current density. Once the diffusion layer is established, the growth of the wires takes place inside the porous AAO membrane. The current density is quasistatic during the pore filling. The kinetic energy for the diffusion of metal ions comes from the action of the electric field. Optical image of AAO membranes before and after FeCo deposition is also given.

by LZ-TEM (ThermoFisher Talos F200S) and SNVM (Diamond-III, CIQTEK). The ferromagnetic resonance testing was conducted under the conditions of 25–30 GHz with an external magnetic field of 0–4000 Oe. The testing platform was self-built, featuring a signal generator (SG, Rohde & Schwarz, smb100a) as the core instrument.

The FORC curves of the sample were acquired using a VSM. The measurement procedure was as follows: Initially, a magnetic field of +5 kOe was applied to fully saturate and magnetize the sample. Subsequently, the field was decreased to a reverse value defined as H_a , and the magnetization curve from H_a to +5 kOe was recorded. This process was repeated by progressively applying new H_a values, and the corresponding magnetization curves were collected, continuing until H_a reached −5 kOe. Typically, approximately 51 magnetization curves were obtained in this manner. The magnetization response in the FORC measurements can be described as $M(H_a, H_b)$, where H_a represents the initial reversal field and H_b denotes the applied magnetic field. The FORC distribution diagram $\rho(H_a, H_b)$ was obtained by second-order bias of H_a, H_b [25, 26]

$$\rho(H_a, H_b) = -\frac{1}{2} \frac{\partial^2 M(H_a, H_b)}{\partial H_a \partial H_b} \quad (1)$$

where $\rho(H_a, H_b)$ represents the probability of $M(H_a, H_b)$ in the FORC diagram. Coordinate transformation of $\rho(H_a, H_b)$: $H_u = (H_a + H_b)/2$ and $H_c = (H_b - H_a)/2$, and the functions of coercive force field H_c and interaction force field H_u were obtained [27].

Micromagnetic simulations were carried out to study the static and dynamic properties of nanowire arrays by using one of widely used micromagnetics simulation software (called object-oriented micromagnetics framework (OOMMF)). The simulation parameters of FeCo nanowires for the dynamic and static simulations are set as: M_s : 19×10^5 A/m, exchange constant A : 27×10^{-12} J/m, and magnetocrystalline anisotropy constant K_1 : 5×10^4 J/m³. A cubic cell size is set as $2 \text{ nm} \times 2 \text{ nm} \times 2 \text{ nm}$, which is smaller than the critical exchange length (2.5 nm for FeCo). The geometric dimensions of “3 × 1” nanowires square array in simulation are: length L : 200 nm; diameter D : 10–50 nm; and center to center spacing s : 65 nm.

3 Results and discussion

Figure 2 summarizes the morphology, structure, and composition

of representative $\text{Fe}_{67}\text{Co}_{33}$ nanowires with $D = 20$ nm. A cross-sectional view of the AAO template after deposition is shown in Fig. 2(a). Because FeCo nanowires have better conductivity than Al_2O_3 , the contrast reveals that more than 15 μm of FeCo nanowires is filled within the 20-micrometer-thick AAO template. The length of the nanowires can be controlled by the deposition time. To prevent the FeCo material from forming a continuous film on the surface of the AAO template, which could affect the magnetic properties of the nanowires, the filling rate of the nanowires is controlled at around 90%. After template removal, Fig. 2(b) reveals that the nanowires are of uniform length. However, due to inter-wire magnetic interactions, they aggregate at their ends. This observation underscores that for 20 nm diameter nanowires, maintaining their arrayed structure for device integration requires them to be embedded within the AAO template.

The specific crystal structure and crystallinity of the nanowires were characterized by dispersing them after dissolving the AAO template and analyzing them via HRTEM. Figure 2(c) shows a TEM image of multiple dispersed nanowires, confirming that the nanowires have a straight morphology with good diameter uniformity. A HRTEM image (Fig. 2(d)) reveals clear lattice fringes. The interplanar spacing measured in the yellow-framed region in Fig. 2(e) is approximately 0.2035 nm, corresponding to the (110) plane of body-centered cubic (bcc) $\text{Fe}_{67}\text{Co}_{33}$ alloy. The directions of (110) crystal planes are indicated by white arrows, and the direction of the red dashed arrow indicates the orientation along the length (long axis) of the nanowire. The angle between the white line and the red line is about 45°, indicating that the nanowire grows along the (001) direction. The elemental mapping of a single nanowire in Fig. 2(f) confirms the homogeneous distribution of Fe and Co, with an approximate atomic ratio of 2:1. Figures 2(g) and 2(h) presents HRTEM images of individual $\text{Fe}_{67}\text{Co}_{33}$ nanowires with diameters of 30 and 40 nm, respectively. A different direction of (110) crystal plane outlined by a white dashed box is observed in 30 nm diameter nanowires, as marked by the white arrows. As the diameter increases to 40 nm, the entire nanowire composed of randomly distributed (110) crystal orientations. To further verify the crystal phase, X-ray diffraction (XRD) analysis was additionally performed on 40-nm-diameter $\text{Fe}_{67}\text{Co}_{33}$ nanowires, as presented in Fig. S2 in the ESM. The diffraction pattern exhibits characteristic peaks of the bcc structure. A peak fitting analysis was conducted in the range of 43°–47°, confirming the FeCo bcc(110) contribution.

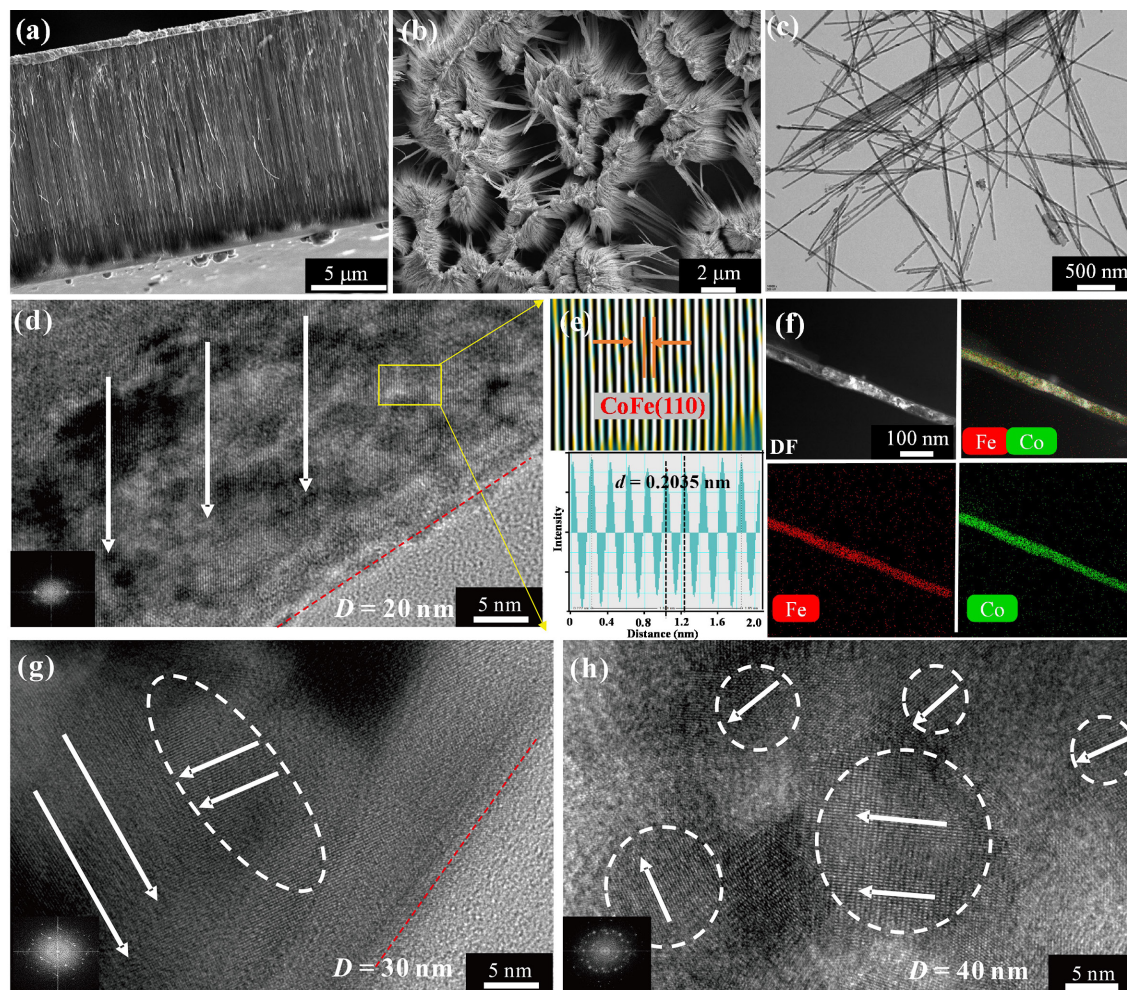


Figure 2 (a) Cross-sectional SEM image of the AAO template after nanowire deposition. (b) SEM image of the FeCo nanowire after removing AAO template. (c) TEM image of dispersed nanowires. (d) HRTEM image of a single 20 nm nanowire. (e) Inverse fast Fourier transform (IFFT) and corresponding lattice spacing measurement. (f) Elemental mapping of a single 20 nm nanowire. (g) HRTEM image of a single 30 nm nanowire. (h) HRTEM image of a single 40 nm nanowire. The (110) crystal planes with different orientations are outlined by white dashed boxes, and their orientation directions are indicated by white arrows. The direction of the red dashed arrow indicates the orientation along the length (long axis) of the nanowire.

This result further supports the bcc crystalline structure identified by HRTEM.

Figures 3(a)–3(c) present the magnetic hysteresis loops of $\text{Fe}_{67}\text{Co}_{33}$ nanowire arrays with diameters (D) of 20, 30, and 40 nm, measured with the field applied parallel and perpendicular to the wire axis. A clear trend emerges: Both the SQ and H_c in the parallel direction decrease monotonically as D increases. This indicates a gradual deterioration of the uniaxial magnetic anisotropy and reversal hardness, which are desirable for device applications. The underlying mechanism of this trend is jointly governed by the inter-wire spacing S (defined as the edge-to-edge distance between adjacent nanowires) and the nanowire diameter. Here, regardless of whether the pore diameter is 20, 30, or 40 nm, the center-to-center spacing of the template pores is fixed at 65 nm. The ratio S/D , which dictates the dominant inter-wire interaction, decreases from 2.25 (20 nm) to 1.16 (30 nm) to 0.625 (40 nm). According to established models [28], an S/D more than 1 favors weaker exchange interactions, while S/D less than 1 leads to strong magnetostatic (dipolar) coupling. Consequently, with increasing D , the enhanced dipolar interaction promotes lateral alignment of magnetic moments between neighboring nanowires. This lateral

coupling directly competes with the preferred longitudinal alignment dictated by shape anisotropy, thereby reducing the SQ. Furthermore, these strengthened inter-wire dipolar fields provide additional nucleation sites and reversal pathways for magnetization switching, which effectively lowers the measured H_c . Thus, diameter control emerges as a direct method to tune the strength and nature of magnetic interactions within the array, with immediate consequences for key static magnetic properties.

To further investigate the magnetic interactions and domain states in FeCo nanowires, we studied the influence of nanowire diameter using FORC measurements. Figures 3(d)–3(f) show the FORC diagrams for $\text{Fe}_{67}\text{Co}_{33}$ nanowires with the magnetic field applied parallel to the wire axis. The red regions indicate a higher switching probability. In general, the H_c axis in a FORC diagram reflects the distribution of coercivities, while the H_u axis represents the distribution of magnetostatic interaction fields. For SD behavior, the H_c distribution is symmetric and shifted away from zero, with contour lines clustered along the H_c axis [29, 30]. In contrast, MD systems typically exhibit a major H_c peak near 0 mT, accompanied by an open elliptical contour pattern centered along the H_u axis. As shown in Fig. 3(g), at $D = 20$ nm, the H_c

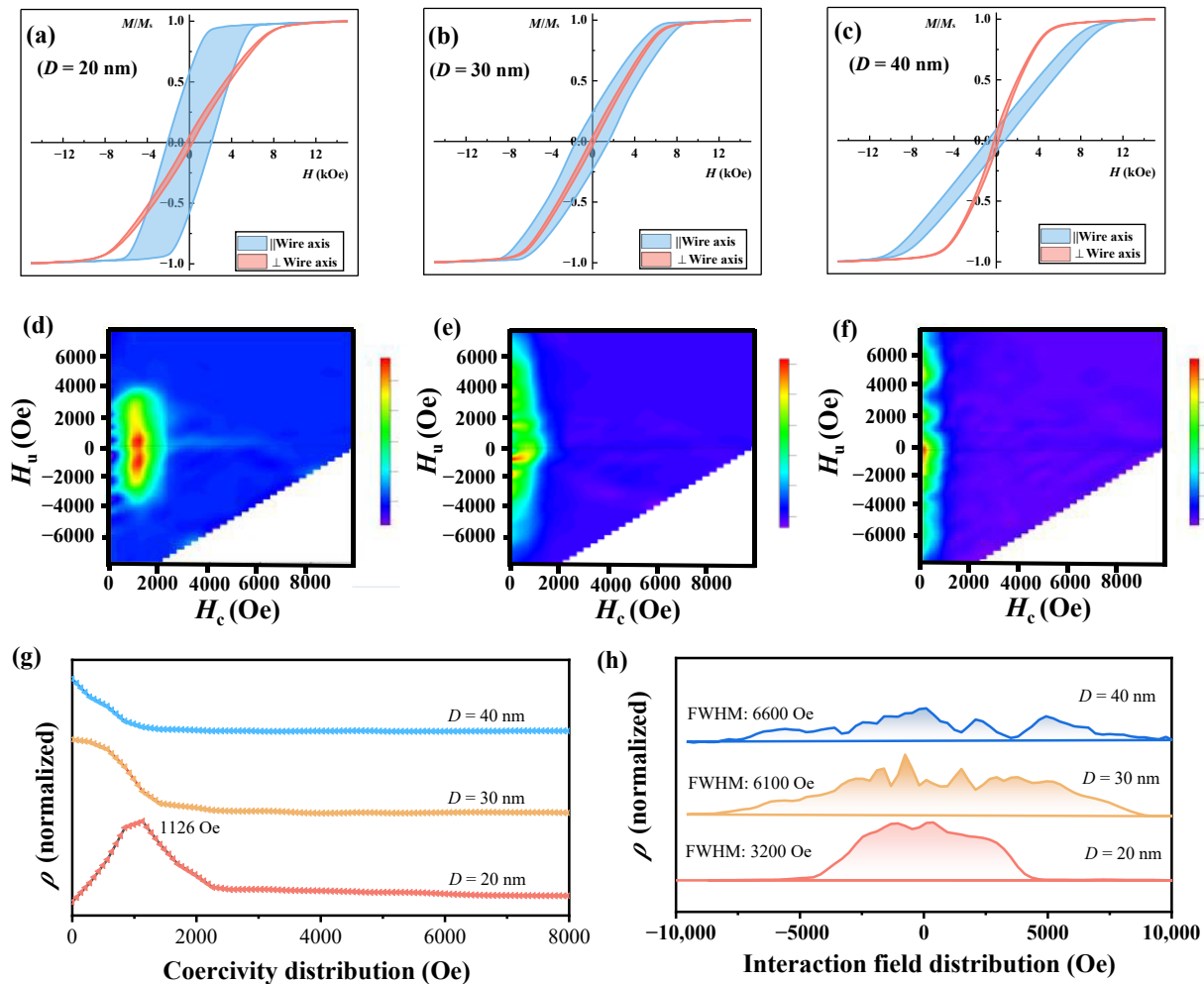


Figure 3 Hysteresis loops of $\text{Fe}_{60}\text{Co}_{33}$ alloy nanowire with different diameters: (a) 20, (b) 30, and (c) 40 nm. The FORC diagrams of $\text{Fe}_{60}\text{Co}_{33}$ alloy nanowire: (d) 20, (e) 30, and (f) 40 nm. (g) Coercivity distribution at $H_u = 0$. (h) Interaction field distribution through the maximum FORC probability (red regions) of FeCo nanowires at different diameters. The coercivity distribution peaks are given in (g), and any unreported values default to zero. The FWHM of the interaction field distribution is also given in (h).

distribution is symmetric and shifted away from zero, center at $H_c^{\text{FORC}} = 1126$ Oe, with contour lines clustered along the H_c axis. As the diameter increases, the region of highest FORC distribution probability shifts leftward along the H_u axis (near $H_c^{\text{FORC}} = 0$ Oe), suggesting a transition from SD to MD behavior. Additionally, the interaction field distribution is characterized by the full width at half maximum (FWHM) of the FORC distribution cut through the main peak along the H_u direction. This FWHM is widely considered a measure of the local interaction field among magnetic entities. The FeCo nanowire with high D values exhibits a high H_u distribution, implying stronger interwire interactions. The observed shift of the FORC distribution toward $H_c \approx 0$ and the broadening along the H_u axis with increasing diameter are consistent with a transition from SD to MD behavior, as previously inferred from FORC diagrams in FeCo, Ni, and Fe nanowire arrays [6, 17, 18]. The increase in the FWHM of the interaction field distribution (Fig. 3(h)) quantitatively confirms that the inter-wire magnetostatic coupling becomes stronger as the edge-to-edge distance decreases with larger diameter. This trend agrees with the model for FeNi and Ni nanowire arrays [13, 15].

The magnetic domains of nanowires were also characterized by LZ-TEM, as shown in Fig. 4. The series of LZ-TEM images display two sets of nanowires with diameters of 40 and 20 nm, respectively,

captured under three different defocus conditions: in-focus, under-focus, and over-focus. For the 40 nm diameter nanowire, the images reveal a clear variation in contrast, bright and dark fringes, across the nanowire's length when viewed in under-focus and over-focus conditions. The upper-right insets present a rendered visualization of magnetic domains, with green and red regions corresponding to distinct magnetic orientations. This contrast originates from electron-beam deflection due to magnetic induction within the sample, a well-established contrast mechanism in Fresnel-mode Lorentz transmission electron microscopy [31, 32]. Alternating bright and dark regions reflect local variations in the induction direction, confirming a multi-domain configuration in which magnetization is segmented into regions separated by domain walls. Such a structure is typical in larger-diameter nanowires, where the reduction of magnetostatic energy favors domain subdivision. In stark contrast, the 20-nm-diameter nanowire exhibits uniform brightness and negligible contrast variation across all three defocus conditions. This homogeneous Lorentz signal indicates a single-domain state, with magnetization aligned uniformly along the nanowire axis and no domain walls present. At this reduced diameter, the nanowire dimensions fall below the critical size for domain wall stabilization, allowing exchange interactions to dominate and maintain a coherent

magnetic structure. The direct comparison underscores a clear diameter-dependent transition in magnetic configuration: The 40 nm nanowire adopts multiple domains to minimize magnetostatic energy, whereas the 20 nm nanowire remains single-domain as a consequence of size limitation.

Additionally, the under-focus and over-focus images enhance the visibility of magnetic structures by highlighting areas where magnetic fields diverge or converge, making domain walls and internal magnetization changes more apparent. In the 40 nm nanowire, these defocused images accentuate the domain boundaries, while in the 20 nm nanowire, the uniform contrast further confirms the absence of such structures. In summary, LZ-TEM in defocus mode serves as a powerful tool for visualizing

magnetic domains in nanoscale materials. The observed differences between the 40 and 20 nm nanowires demonstrate a transition from multi-domain to single-domain magnetic behavior as the diameter decreases, a key aspect in the design of magnetic nanomaterials for applications in spintronics and data storage.

Figure 5 characterizes the magnetic domain structures of $\text{Fe}_{67}\text{Co}_{33}$ nanowires through SNVM. The working principle of SNVM is illustrated schematically in Fig. 5(a), which relies on a diamond NV center [33]. The NV center comprises a substitutional nitrogen atom paired with an adjacent lattice vacancy, forming a photostable luminescent defect with a spin-triplet ground state ($S = 1$). When excited optically by a 532 nm laser, the center can be polarized into the $m_s = 0$ spin sublevel. Its spin state is subsequently read out by

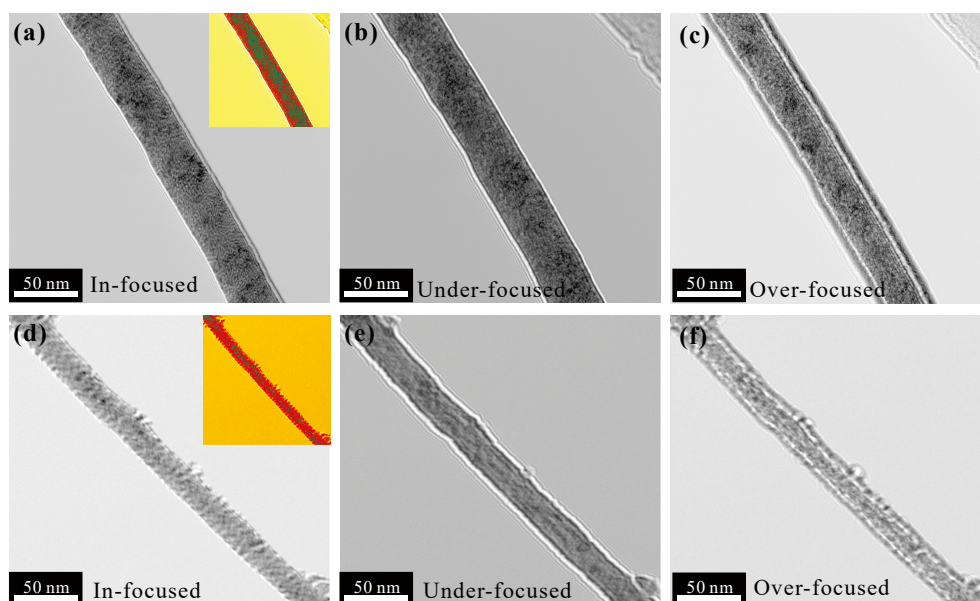


Figure 4 Lorentz images of $\text{Fe}_{67}\text{Co}_{33}$ alloy nanowire at diameter of 40 and 20 nm: ((a) and (d)) in-focused, ((b) and (e)) under-focused, and ((c) and (f)) over-focused. The insets in the upper right corners are magnetic domain rendering, where the colors green and red represent different magnetic domains.

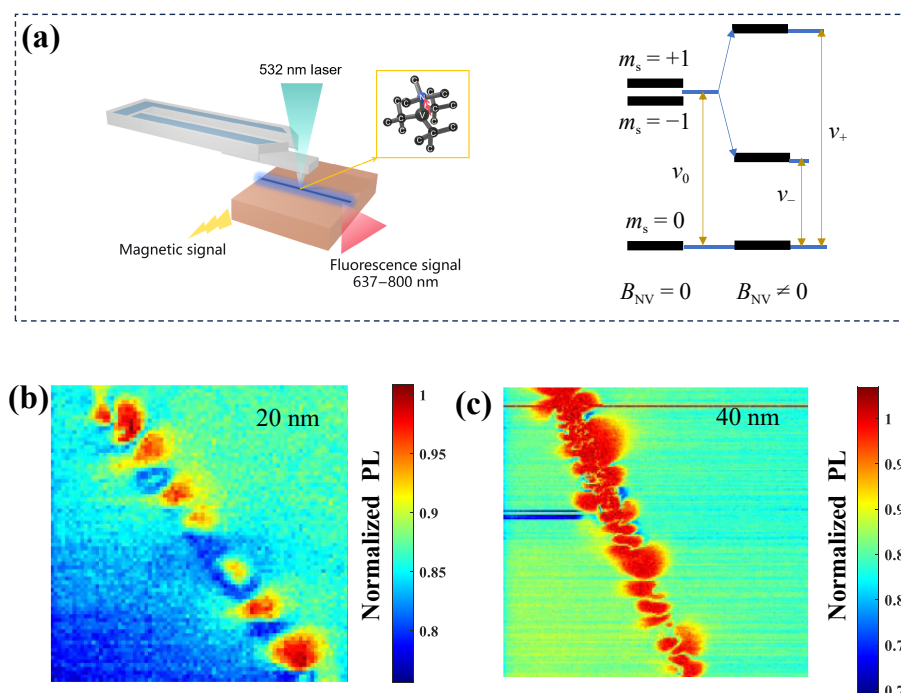


Figure 5 (a) A schematic diagram of the SNVM. ((b) and (c)) The magnetic domain images of the $\text{Fe}_{67}\text{Co}_{33}$ nanowire by SNVM for (b) 20 and (c) 40 nm.

monitoring the photoluminescence (PL) intensity within the 637–800 nm band: The $m_s = \pm 1$ states yield a lower PL intensity than the $m_s = 0$ state [34, 35]. This property enables the optical detection of microwave-driven spin resonances, thereby permitting nanoscale magnetic imaging.

Normalized PL profiles acquired along individual nanowires reveal distinct magnetic configurations that depend on nanowire diameter. For the 20 nm nanowire (Fig. 5(b)), the PL signal displays a clear red–blue quasiperiodic modulation along its axis. Such alternating contrast reflects a periodic reversal of the local magnetization, consistent with an SD structure in which the magnetization direction flips along the wire length, a finding that aligns with earlier LZ-TEM results. By contrast, the PL profile for the 40 nm nanowire (Fig. 5(c)) exhibits more complex and aperiodic variations and lacks the regular modulation observed in the thinner wire. This irregular magnetic pattern suggests the formation of multiple magnetic domains, confirming a transition to a multi-domain state in nanowires of larger diameter.

The LZ-TEM images (Fig. 4) directly reveal the transition from a nearly uniform contrast (20 nm) to alternating bright/dark contrast (40 nm), indicating the presence of multiple magnetic domains in the larger-diameter wires. The SNVM profiles (Fig. 5) further support this interpretation: The 20 nm nanowire shows a regular periodic modulation of the photoluminescence signal consistent with a single-domain structure, while the 40 nm nanowire exhibits a more complex and aperiodic pattern characteristic of a multi-domain configuration. While previous studies have inferred such a diameter-driven SD–MD transition from FORC and hysteresis loop analysis, the combination of LZ-TEM and SNVM here provides complementary real-space visualization of this transformation in FeCo nanowires. The consistency across multiple independent techniques (macroscopic loops, FORC, LZ-TEM, and SNVM) reinforces the conclusion that the critical diameter for the SD–MD transition in these FeCo nanowires lies near 30 nm.

To elucidate the effect of nanowire diameter on magnetic properties, we performed micromagnetic simulations of magnetization reversal in nanowires with D from 10 to 50 nm. Figure 6(a) presents the axial hysteresis loops for nanowires with diameters from 10 to 50 nm, while Figs. 6(b) and 6(c) show the corresponding SQ and H_c , respectively. Consistent with experimental trends, both SQ and H_c decrease with increasing diameter. H_c decreases nearly linearly, whereas SQ declines gradually up to 30 nm and then drops sharply, reflecting a transition from SD to MD structures.

Figure 6(d) and Fig. S3 in the ESM show top and cross-sectional views of the two dominant magnetization switching modes for the 20, 30, and 40 nm nanowires. In all cases, reversal follows the same sequence [36]: The two outer nanowires switch first, followed by the central one. At 20 nm, the outer nanowires reverse via a symmetric mode involving the formation and propagation of reversed domains. At 40 nm, this transitions to an asymmetric and more complex switching mode.

Additionally, three established reversal mechanisms are considered [21, 22, 37]: coherent rotation mode (CRM), in which magnetic moments rotate uniformly; transverse reversal mode (TM), involving progressive magnetization reversal via transverse domain wall propagation; and vortex reversal mode (VM), characterized by a curling-type domain wall and non-uniform moment alignment. As the nanowire diameter increases, the relaxation of geometrical confinement enables the development of more complex spin configurations during reversal. In smaller-diameter nanowires, the restricted cross-sectional area favors quasi-uniform spin alignment, leading to transverse-mode-dominated reversal. By contrast, larger diameters provide sufficient space for curling and vortex-like structures to emerge, thereby promoting a transition toward vortex-dominated reversal mechanisms. Typically, modes propagating in CRM and TM modes are predominantly single-domain structures, while those propagating

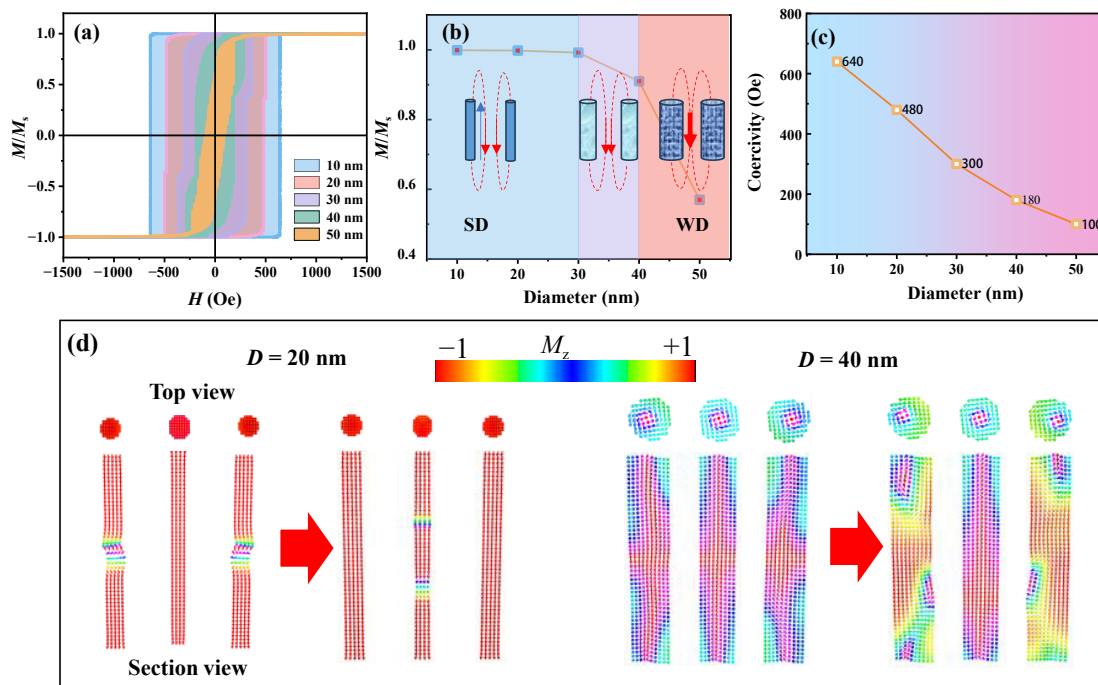


Figure 6 (a) The simulated hysteresis loops for diameters ranging from 10 to 50 nm. (b) The schematic of a magnetic interaction effect between parallel nanowires, illustrating the corresponding variation trend of SQ, and (c) presenting the variation trend of H_c . (d) Top and section views of the primary magnetization switching states for nanowires with diameters of 20 and 40 nm.

in VM mode are mainly multi-domain structures. Here, the simulation results indicate that the 20 nm propagates in TM mode, while the 40 nm propagates in VM mode, suggesting a single-domain structure for the 20 nm sample and a multi-domain structure for the 40 nm sample. These findings are in agreement with the experimental measurements. The simulated switching mode transition from TM to VM as the diameter increases aligns with the experimental observation of reduced coercivity and squareness. This behavior is governed by the changing balance between exchange and magnetostatic energies, as well as the increased dipolar coupling when the inter-wire spacing-to-diameter ratio (S/D) falls below unity, a concept well established in FeCo and Ni nanowire arrays [6, 15].

To investigate the effect of diameter from a dynamic perspective, we conducted micromagnetic simulations to obtain the ferromagnetic resonance (FMR) spectra of the nanowire arrays. The magnetic spectra (Fig. 7) clearly demonstrate the influence of nanowire diameter variation on their dynamic magnetic response. For a single nanowire, as the diameter increases, the number of resonance peaks increases from 2 to 8. This phenomenon directly reflects the evolution of its internal magnetic structure from a single-domain state to a multi-domain state [38]. At smaller diameters (e.g., 10 and 20 nm), a single resonance peak dominates the spectrum, corresponding to coherent precession modes under uniform magnetization or a simple vortex state [39]. However, when the diameter increases to 30 nm and beyond, multiple additional resonance peaks emerge. These multi-peak structures originate from the local resonance characteristics of different magnetic domains or complex non-uniform magnetization configurations (such as transverse domain walls), where each region

resonates at different frequencies due to its unique effective field environment. Thus, the increase in the number of peaks serves as direct spectroscopic evidence of the formation of a multi-domain structure within the nanowire.

When comparing the spectra of a single nanowire and an array of three nanowires, the influence of magnetic dipole interactions becomes critical [40]. At smaller diameters (10 and 20 nm), the spectra of the three nanowires are nearly identical to that of the single nanowire, indicating weak magnetic coupling between the nanowires due to their relatively large spacing, placing them in a nearly magnetically decoupled state. However, when the diameter increases to 30 nm, the number of resonance peaks in the triple-nanowire array increases sharply compared to the single-nanowire case, rising from 6 to 14. This abrupt change marks the onset of strong inter-wire coupling dominating the magnetic dynamics of the system. A larger diameter means that each nanowire possesses a stronger magnetic moment and stray field, sufficient to significantly perturb the magnetic configuration of adjacent nanowires. This coupling not only alters the domain structure within individual nanowires but also excites collective resonance modes involving multiple nanowires and introduces new localized modes at the adjacent edges of the nanowires, leading to a substantial increase in spectral complexity. The emergence of multiple resonance peaks with increasing diameter provides spectroscopic evidence of the evolving domain structure, complementing the static magnetic measurements. The clear increase in the number of peaks when moving from a single nanowire to a three-nanowire array at diameters of 30 nm and above indicates the onset of significant inter-wire coupling, which can complicate the dynamic response. These observations highlight the importance of diameter control

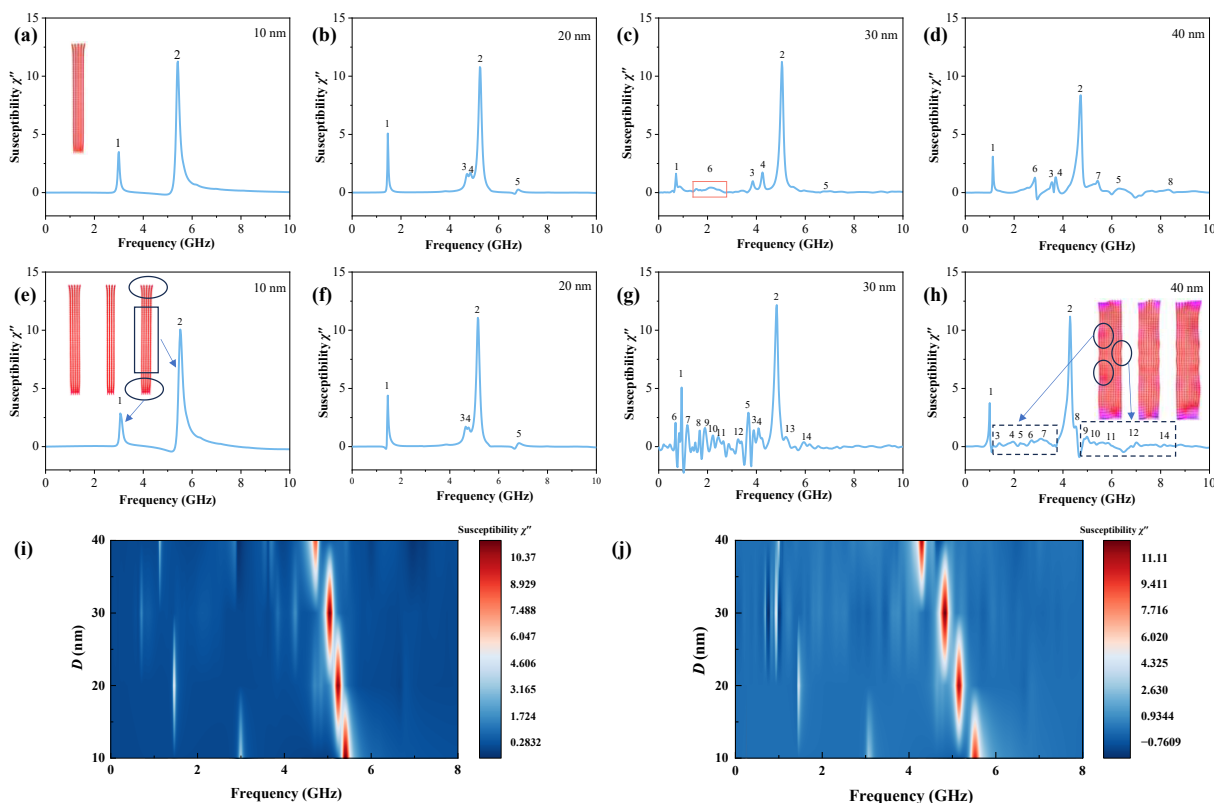


Figure 7 Diameter-dependent ferromagnetic resonance spectra revealing the onset of multi-domain structures and intensified inter-wire coupling. ((a)–(d)) Dynamic magnetic spectra of a single nanowire with varying diameters. ((e)–(h)) Dynamic magnetic spectra of nanowire arrays with varying diameters. ((i) and (j)) Resonance peak frequency as a function of nanowire diameter: (i) single nanowire and (j) nanowire arrays.

not only for static magnetic properties but also for tailoring the high-frequency behavior of nanowire arrays.

Furthermore, it can be observed from the figure that as the nanowire diameter increases, the two primary resonance peaks (peaks 1 and 2) systematically shift toward lower frequencies. This behavior is primarily attributed to changes in shape anisotropy. The resonance frequency of the nanowire is governed by the Kittel equation [41]

$$f = \frac{\gamma}{2\pi} \sqrt{(H_{\text{ext}} + (N_y - N_x)M_s)(H_{\text{ext}} + (N_z - N_x)M_s)} \quad (2)$$

where N_x , N_y , and N_z are the demagnetizing factors. For nanowires with high aspect ratios, the demagnetizing factor along the long axis (N_x) is close to zero, while the transverse demagnetizing factors (N_y and N_z) are significantly larger, resulting in a strong shape anisotropy field. As the diameter increases, the transverse demagnetizing factors change, weakening the overall shape anisotropy field. This reduction in the effective field H_{eff} leads to a red shift of the resonance frequency. Typically, peak 2 corresponds to the quasi-uniform “bulk” precession mode, which is most sensitive to the overall shape anisotropy, while peak 1 is often associated with the localized “edge” mode arising from the inhomogeneous demagnetizing field at the ends of the nanowire [42]. The frequency shifts of both peaks collectively document the modification of the magnetic potential landscape due to changes in geometric dimensions. In summary, these dynamic magnetic spectra collectively reveal two core dimensions in nanowire magnetism: the internal structural transition from single-domain to multi-domain driven by increasing diameter, and the subsequent enhancement of inter-nanowire magnetic coupling, which induces complex collective dynamics in arrays. These insights are crucial for the design of nanowire-based spintronic devices and high-frequency magnetic applications.

In addition, we performed FMR measurements on the nanowire samples with 20 nm in diameter using a ferromagnetic resonance spectrometer to evaluate their magnetic properties. Figure 8(a) and

Fig. S4 in the ESM display the FMR spectra of FeCo nanowires in the frequency range of 25–30 GHz. Two distinct resonance peaks were observed when the frequency exceeded 24 GHz, which is consistent with the micromagnetic conclusions. As shown in Fig. 8(b), the gyromagnetic ratio $\gamma/2\pi$ (GHz/T) is derived from the slope of the linear fit between the resonance frequency f_{res} and the resonance field H_{res} , while the intercept corresponds to the FMR frequency at zero external field, based on the resonance peaks observed at low fields. Figure 8(c) presents the linear relationship between the linewidth broadening ΔH and f_{res} , where the slope provides the Gilbert damping constant α and the intercept reflects the inhomogeneous linewidth ΔH_0 , indicative of extrinsic contributions to the magnetization damping.

The gyromagnetic ratio of the FeCo is $\gamma/2\pi = 27.28$ GHz/T, and the zero-field ferromagnetic resonance frequency is 23.26 GHz. From $\gamma = (g\mu_B)/\hbar$ and the gyromagnetic ratio $\gamma/2\pi = 27.28$ GHz/T, the Lande g factor is 1.95. The resonance linewidth ΔH is correlated with the Gilbert damping constant α and the gyromagnetic ratio γ (rad/(s·T)) according to Eq. (3)

$$\Delta H = \Delta H_0 + \frac{4\pi\alpha f}{\gamma} \quad (3)$$

From Fig. 8(c) and Eq. (3), the fitted value of α is 0.012. Because the mass or volume of a single nanowire is difficult to determine with high accuracy, its M_s cannot be directly obtained. To address this issue, parameters derived from FMR measurements are commonly used to estimate M_s . The magnetostatic interactions between magnetic nanowires (MNWs) depend on the ratio of interwire spacing to nanowire diameter, which in this study is equivalent to being proportional to the filling factor (i.e., the porosity) of the template. Specifically, when both shape anisotropy and magnetostatic coupling are taken into account, the effective field of MNW arrays can be expressed as [43]

$$H_{\text{eff}} = 2\pi M_s(1 - 3P) \quad (4)$$

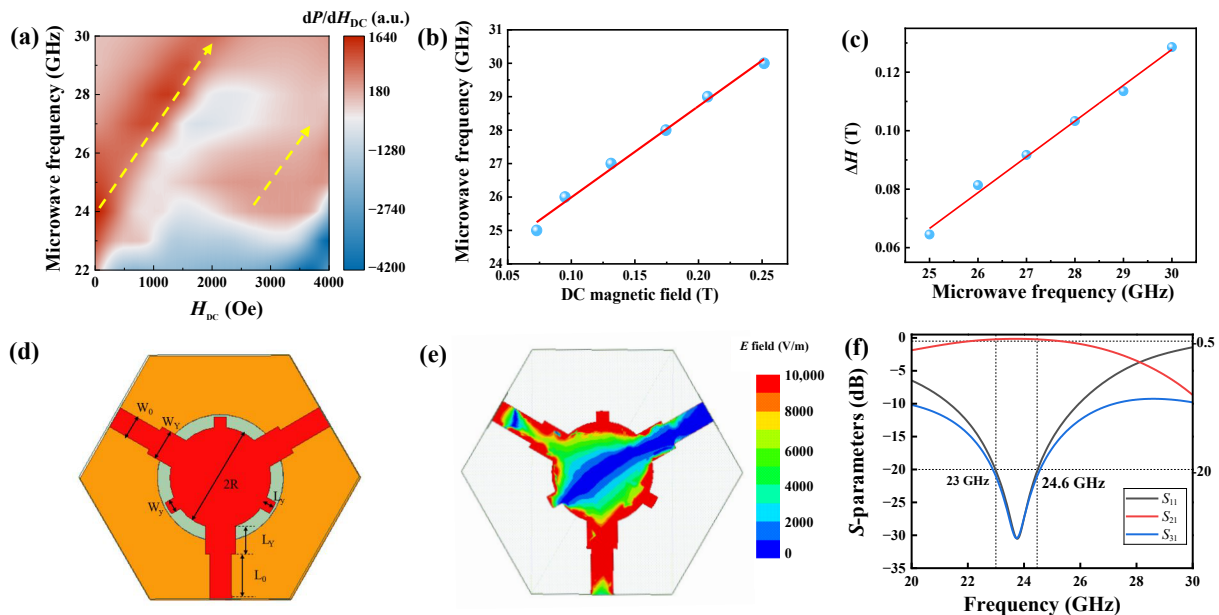


Figure 8 (a) Ferromagnetic resonance absorption spectra of FeCo nanowires in the frequency range of 25–30 GHz. (b) The fitting curve between f_{res} and H_{res} . (c) The linear fitting curve of the linewidth variation ΔH versus f_{res} . (d) Y-junction circulator model. (e) Field pattern of the Y-junction circulator. (f) Simulated S-parameters of the Y-junction circulator.

where P represents the porosity of the template in which the MNWs are embedded. This relation can be validated in the limiting cases: for $P = 0$ (single nanowires), $H_{\text{eff}} = 2\pi M_s$, whereas for $P = 1$ (films), $H_{\text{eff}} = -4\pi M_s$ [41, 44]. The values of H_{eff} in this work are positive since our fill factors were 8.6%. Here, $H_{\text{eff}} = 8526$ Oe. Based on this, the $4\pi M_s$ is calculated to be 2.298 T, which is very important for the subsequent design of circulators.

Based on the above obtained measurement data for the nanowire sample, the following parameters were adopted: saturation magnetization ($4\pi M_s = 2.298$ T), relative permittivity ($\epsilon = 9.2$), and Landé g -factor ($g = 1.95$). A Y-junction circulator was subsequently designed and simulated using high frequency structure simulator (HFSS) [45]. As shown in Fig. 8(d), the composite structure has a total thickness of 450 μm , consisting of a 400 μm thick alumina substrate ($\epsilon = 9.8$) and a 50 μm thick nanowire layer. The optimized microstrip line structural parameters are as follows: center conductor radius $R = 1$ mm, input microstrip line width $W_0 = 0.6$ mm and length $L_0 = 0.907$ mm, Y-junction arm width $W_Y = 0.6$ mm and length $L_Y = 0.5$ mm, and branch width $W_y = 0.25$ mm and length $L_y = 0.2$ mm. The simulated field pattern and S-parameters of the circulator are presented in Figs. 8(e) and 8(f). The results indicate that within the frequency range of 23–24.6 GHz, both isolation and return loss are better than 20 dB, while the insertion loss is less than 0.5 dB. These simulation results demonstrate that the circulator fabricated using this nanowire composite material can achieve effective circulation in the 23–24.6 GHz band. This finding provides valuable guidance for the selection and optimization of magnetic materials for self-biased circulator applications, particularly in identifying nanowire composite systems with suitable magnetic performance and microwave compatibility.

4 Conclusions

In summary, this work presents a multi-scale experimental and computational analysis of diameter-dependent magnetic properties in FeCo nanowire arrays, linking static domain configurations, inter-wire magnetostatic interactions, dynamic resonance behavior, and device-level circulator simulation. A transition from a multi-domain to a single-domain state is observed when the diameter is reduced below approximately 30 nm, as directly visualized and quantified by complementary techniques. This transition is accompanied by enhanced shape anisotropy, increased coercivity, and reduced inter-wire magnetostatic interactions. Micromagnetic simulations further indicate that larger diameters, while supporting multi-domain structures, introduce more complex collective dynamics and stronger inter-wire coupling, which may be less favorable for device stability and signal integrity. From ferromagnetic resonance measurements, key dynamic parameters (gyromagnetic ratio and damping constant) are extracted, and the saturation magnetization is derived using an effective field model. These experimentally determined parameters are then used to simulate a Y-junction circulator, demonstrating the potential of this material system for self-biased microwave applications. Based on these results, a design guideline emerges: For applications that benefit from stable and well-isolated magnetic moments, such as self-biased circulators, nanowire diameters should be kept below the critical size for single-domain formation (~ 30 nm for the present alloy). Conversely, the richer dynamic behavior of larger-diameter arrays may be of interest for other areas such as magnonics or sensing. Overall, the consistency across multiple

experimental and theoretical approaches supports the reliability of the observed diameter-dependent magnetic behavior and provides a basis for further development of FeCo nanowire arrays in high-frequency and spintronic devices.

Electronic Supplementary Material: Supplementary material (SEM characterization of AAO templates and nanowire diameters, XRD structural analysis with peak fitting, micromagnetic simulation of magnetization reversal, and FMR measurement setup and spectra, and Figs. S1–S4) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908911>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

H. Z.: Data curation, project administration, validation, writing manuscript, experimental design, funding acquisition. Y. Y. L.: Data curation, validation, experimental design, writing manuscript. Y. Z. L.: Data curation. Z. C. W.: Validation. Y. H. W.: Resource. L. J. D.: Resource, project administration. All the authors have approved the final manuscript.

Use of AI statement

None.

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