

Article

Annealing and Thickness-Dependent Structural, Magneto-Optical, and Ferromagnetic Resonance Properties of RF-Sputtered YIG/GGG Thin Films

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Featured Application

Potential application: selection of annealing temperature and film thickness for RF-sputtered YIG/GGG layers used in magneto-optical and microwave experiments.

Abstract

Yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, YIG) films were deposited on gadolinium gallium garnet ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$, GGG) through room-temperature RF magnetron sputtering and annealed in flowing oxygen. We examined the effects of annealing temperature and film thickness using X-ray diffraction (XRD), scanning electron microscopy (SEM), longitudinal magneto-optical Kerr effect (MOKE) loops and multi-frequency field-swept ferromagnetic resonance (FMR). Representative SEM images showed laterally uniform surface backgrounds with sparse localized particulates. Gaussian switching-field fits with residual-bootstrap analysis were used to obtain Kerr-derived coercive fields, switching-field standard deviations and their normalized ratios. In the temperature series, the 900 °C sample gave the smallest fitted σ_{SFD}/H_c , whereas the 850 °C sample gave the lowest effective damping of $\alpha = (4.2 \pm 0.27) \times 10^{-3}$. In the thickness series annealed at 850 °C, the 75 nm film combined the smallest σ_{SFD}/H_c ($3.11 \pm 0.38\%$) with the lowest measured α , $(5.84 \pm 0.16) \times 10^{-3}$. The different temperature optima show that switching uniformity and dynamic loss should be assessed separately. The results provide an empirical comparison for selecting processing conditions within the investigated RF-sputtered YIG/GGG series.

Keywords: yttrium iron garnet; RF magnetron sputtering; magneto-optical Kerr effect; ferromagnetic resonance; Gilbert damping; switching-field distribution



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1. Introduction

Yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, YIG) combines exceptionally low magnetization damping, low coercivity, low microwave loss and long magnon-propagation lengths [1–4]. These properties underpin microwave and magneto-optical devices, including isolators, circulators, resonators and magnetic sensors [5–8]. High-quality epitaxial YIG films also enable spin current and spin caloritronic studies [9–13], spin transfer torque devices [14], magnetic logic units [15,16], magneto-optical memory [17] and spin torque FMR measurements in YIG/ferromagnetic metal heterostructures [18]. Magnetic logic units depend on low-loss

spin-wave transmission and well-defined magnetic bias states [15,16], whereas magneto-optical memory requires reproducible field-driven reversal and optical readout [17].

Gadolinium gallium garnet ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$, GGG) is the most widely used substrate for nanoscale YIG because the two garnets have closely matched cubic lattice constants. Bulk values of approximately 12.383 Å for GGG and 12.376 Å for YIG correspond to a nominal mismatch of about 0.06%. This small mismatch supports oriented growth and post-deposition recrystallization of YIG on GGG(111). It also causes the YIG(444) and GGG(444) reflections to lie close together, which complicates structural interpretation when the YIG layer is thin.

GGG also participates in the magnetic environment of nanoscale YIG. Interfacial structure, strain relaxation and substrate-dependent anisotropy can shape garnet-film magnetodynamics [4,19]. This point becomes particularly important at cryogenic temperatures: recent YIG/GGG studies show that the paramagnetic GGG substrate produces an inhomogeneous stray field and additional wavenumber-dependent magnon loss, both relevant to quantum-magnonic operation [20–22]. At room temperature, close lattice matching remains the main reason for selecting GGG(111) as a reference substrate for process-dependent YIG properties.

High-quality nanoscale YIG has been prepared using liquid-phase epitaxy (LPE), pulsed laser deposition (PLD), chemical routes and magnetron sputtering [19,23–36]. LPE provides benchmark low damping and excellent crystal quality, particularly for thicker epitaxial films, but melt growth is less convenient for ultrathin thickness control and lithographic integration [33,34]. PLD can produce high-quality ultrathin YIG with good composition control, although laser-vacuum processing and limited coating area constrain scalability [27–29,33,36]. Chemical routes can reduce equipment demands and support scalable coating, but phase purity, thickness control and post-crystallization remain sensitive to precursor chemistry [23–26]. RF sputtering is comparatively low in cost among vacuum physical-deposition methods, widely available, and compatible with uniform large-area deposition and lift-off patterning, but room-temperature-grown YIG generally requires high-temperature post-annealing and a careful control of stoichiometry [25,31,32,35,37]. Separating precursor deposition from garnet crystallization therefore makes RF sputtering attractive for the present study.

For room-temperature-sputtered YIG, the as-deposited precursor is commonly amorphous or weakly ordered, making the annealing step decisive for garnet formation [3,38,39]. The annealing temperature governs crystallization, defect evolution and the resulting magnetic response. Sputtered YIG studies have linked FMR linewidth to crystallinity, surface morphology and magnetic inhomogeneity, with non-monotonic dependences on annealing temperature and thickness [40,41]. Stoichiometry also influences the microwave response of sputtered YIG [42]. Film thickness introduces a second control variable by changing magnetic volume, relative interface contribution and strain relaxation. Annealing temperature and thickness therefore define a practical two-parameter space for tuning structural order, reversal uniformity and microwave damping.

YIG-based magnonic memory and logic architectures illustrate the need to assess both microwave response and reproducible magnetic-state control [43–45]. Switching-field distributions are established descriptors of reversal uniformity in patterned magnetic media. In epitaxial garnet particle arrays, a Gaussian SFD captures the spread of individual reversal fields caused by local internal fields, defects and thermal activation [46]. More broadly, narrower SFDs reduce transition jitter and bit-error probability in magnetic recording models [47]. In the present continuous YIG films, σ_{SFD}/H_c is used as a dimensionless comparative measure of reversal uniformity: normalizing σ_{SFD} by H_c allows samples with different mean switching fields to be compared on the same relative scale.

MOKE and FMR provide complementary, rather than interchangeable, observables. A longitudinal Kerr loop follows the optically weighted in-plane magnetization component during field reversal. The switching-field standard deviation, σ_{SFD} , describes the width of the reversal-field distribution [46,47]. Low H_c reduces the field required to reach reversal, whereas a small σ_{SFD}/H_c indicates that reversal occurs over a narrow field interval relative to the mean coercive field. Field-swept FMR instead measures resonance and linewidth; the slope-derived α is an effective dynamic loss parameter, and lower α corresponds to slower decay of coherent precession and lower resonant dissipation [1,3,34]. Because these metrics arise from different measurement channels, we compare their process dependences without assuming a direct one-to-one correlation. From an application perspective, Kerr-derived H_c and σ_{SFD}/H_c quantify the field scale and relative uniformity of reversal relevant to reproducible state selection in magnetic logic and memory architectures [15,16,43–47]. The Kerr response provides optical sensitivity to the magnetic state, which underpins magneto-optical readout [17]. The FMR-derived α evaluates effective dynamic loss relevant to microwave and spin-wave signal transmission [1,3,15,16,34].

Here, we map the effects of post-deposition annealing temperature and film thickness on the structural XRD signature, surface SEM morphology, Kerr loop reversal and multi-frequency field-swept FMR response of RF-sputtered YIG/GGG(111). Two controlled sample series prepared on the same deposition platform are compared. The resulting process–property map identifies the conditions that best balance switching uniformity and effective damping within the investigated series.

2. Materials and Methods

2.1. Film Deposition and Post-Annealing

YIG films were deposited at room temperature on GGG(111) substrates using a TRP-450 RF magnetron sputtering system (Shenyang Scientific Instruments Co., Ltd., Chinese Academy of Sciences, Shenyang, China). The chamber base pressure was 2×10^{-5} Pa. During deposition, the RF power was 150 W, the target-to-substrate distance was 60 mm and the Ar working pressure was maintained at 0.9 Pa. Film thickness was adjusted through the deposition time and measured using a DektakXT stylus profiler (Bruker, Tucson, AZ, USA).

Post-deposition annealing was carried out in a rapid thermal annealing furnace (UniTemp GmbH, Pfaffenhofen, Germany). Oxygen was introduced at 1 L min^{-1} for 240 s before heating and was maintained at the same flow during the 2 h anneal. The furnace pressure display was approximately 8.1×10^2 hPa under this flow condition. Two sample sets were prepared. The temperature series comprised 48 nm films annealed at 650, 750, 800, 850 and 900 °C. The thickness series comprised 20, 35, 48, 75, 90 and 120 nm films annealed at 850 °C.

2.2. Structural and Surface Characterization

θ – 2θ XRD measurements were performed using a D/max-3B diffractometer (Rigaku Corporation, Tokyo, Japan) with Cu K α radiation. All annealing temperature and thickness samples were measured around the YIG/GGG(444) region using the same measurement geometry. The film patterns were compared with a bare GGG(111) substrate.

Surface morphology was examined using a GeminiSEM 500 field-emission scanning electron microscope (Carl Zeiss Microscopy GmbH, Oberkochen, Germany). Because YIG/GGG is electrically insulating, a conductive Au coating was applied before imaging to suppress charging. A 48 nm film annealed at 800 °C and a 75 nm film annealed at 850 °C were examined in SE2 mode at an accelerating voltage of 5.00 kV. The 48 nm sample was imaged at $20,000\times$ with a working distance of 4.9 mm. The 75 nm sample was imaged at $200\times$ and $40,000\times$ with working distances of 15.7 and 5.3 mm, respectively. For figure

assembly, only the instrument information footer was cropped; brightness, contrast and gamma were not altered.

2.3. MOKE Measurement and Switching-Field Analysis

Room-temperature magnetic reversal was measured using a home-built longitudinal MOKE system. A 635 nm, 5 mW ULN laser module (Coherent, Inc., Santa Clara, CA, USA) was incident at approximately 45°. The reflected beam passed through a Glan–Thompson prism used as the analyzer. The magnetic field was applied in the film plane, and the sweep range was adjusted for each sample to cover positive and negative saturation.

The reported absorption coefficient of RF-sputtered YIG/GGG at 635 nm is $7.986 \times 10^3 \text{ cm}^{-1}$ [48], corresponding to an absorption-limited 1/e optical path of approximately 1.25 μm . The corresponding surface-normal sampling scale at oblique incidence remains larger than the 20–120 nm film thickness range, allowing the full film thickness to contribute to the measured Kerr response.

Ascending and descending loop branches were fitted with integrated Gaussian switching functions. For each branch, the fitted center x_c represents the mean reversal field and σ represents the width of the corresponding Gaussian derivative. The coercive field was calculated from the two branch centers as $H_c = |x_{c,+} - x_{c,-}|/2$, following established MOKE magnetometry procedures [49–52]. The switching-field standard deviation was calculated as $\sigma_{\text{SFD}} = (\sigma_+ + \sigma_-)/2$, and the normalized distribution was reported as $(\sigma_{\text{SFD}}/H_c) \times 100\%$.

Fit uncertainty was evaluated using 2000 residual-bootstrap refits of each measured loop. The symmetric error bars for the fitted MOKE parameters represent half the width of the corresponding 95% bootstrap interval.

2.4. Multi-Frequency Field-Swept FMR

Room-temperature FMR spectra were acquired using a CryoFMR spectrometer manufactured by NanOsc Instruments AB (Kista, Sweden) and supplied by Quantum Design, Inc. (San Diego, CA, USA). Each film was placed face-down on a coplanar waveguide. The static field was applied in the film plane and perpendicular to the microwave magnetic field. Measurements were made from 3 to 7 GHz in 0.5 GHz increments, using a nominal field step of 2 Oe and a field-modulation frequency of 490 Hz.

The lock-in response was fitted with a derivative Lorentzian function to determine the resonance field and effective linewidth using the same convention for every sample. The in-plane Kittel relation was used to fit the frequency dependence of the resonance field. The effective damping parameter α and zero-frequency inhomogeneous term ΔH_0 were obtained from a linear fit of linewidth versus frequency. The reported uncertainty in α is the regression fit uncertainty.

3. Results and Discussion

3.1. Structural and Surface Characterization of YIG Films

Figure 1a compares the GGG(444) region of the bare substrate with 48 nm films annealed at 800 and 850 °C. The dominant peaks near $2\theta = 51.4\text{--}51.6^\circ$ arise from the $\text{Cu K}\alpha_1$ and $\text{K}\alpha_2$ components of the substrate-dominated (444) reflection. Because YIG and GGG have closely matched lattice constants, the film-associated YIG(444) contribution appears as a weak shoulder beside the intense substrate peak. This shoulder is more pronounced after annealing at 850 °C, consistent with a stronger crystalline YIG contribution at the higher temperature.

The bare substrate and film patterns were acquired using the same geometry, allowing the substrate profile to serve as a reference for the annealing-dependent shoulder. The structural comparison is therefore based on the relative evolution of this film-associated

feature rather than on the width of the substrate-dominated doublet. Its clearer appearance at 850 °C provides structural context for the corresponding improvement in the quasistatic and dynamic magnetic response.

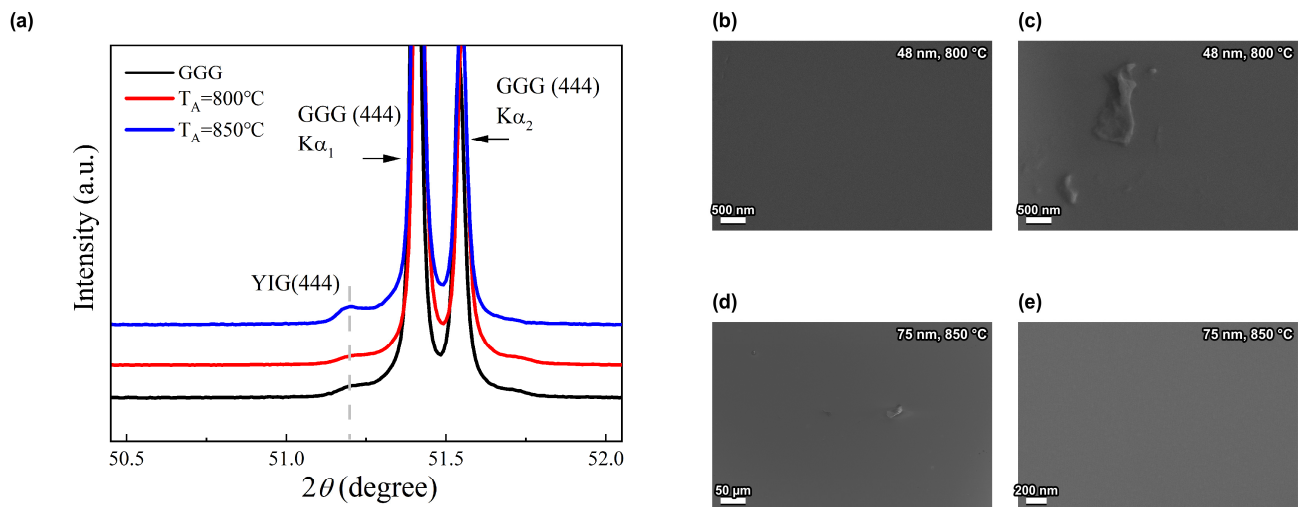


Figure 1. Structural and surface characterization of representative YIG/GGG films. (a) XRD patterns in the YIG/GGG(444) region for the bare GGG substrate and 48 nm films annealed at 800 and 850 °C. (b,c) SE2 SEM images of the 48 nm film annealed at 800 °C, showing a comparatively uniform field and localized protrusions, respectively. (d,e) Low- and high-magnification SEM images of the 75 nm film annealed at 850 °C, showing sparse particulates in the overview and a comparatively uniform surface background at higher magnification. Samples were Au-coated before SEM imaging.

Previous studies of room-temperature-deposited YIG/GGG report the emergence and strengthening of YIG reflections after high-temperature treatment [3,38,39], providing broader context for the annealing-dependent structural evolution observed here.

The SEM images provide complementary surface information. The 48 nm film annealed at 800 °C exhibits broad, comparatively uniform regions at 20,000 $\times$ (Figure 1b), together with isolated micrometer-scale protrusions in an additional field (Figure 1c). The low-magnification overview of the 75 nm film annealed at 850 °C shows sparse isolated particulates across an otherwise continuous surface (Figure 1d), while the 40,000 $\times$ image shows a comparatively feature-poor background (Figure 1e). Thus, the representative films retain lateral surface continuity at the SEM scale, with localized rather than pervasive particulate features.

3.2. Influence of Annealing Temperature

Figure 2a compares the longitudinal Kerr loops of the 48 nm temperature series. The 650 °C film does not merely show a larger switching field; its transition is visibly slanted and broadened, indicating reversal through a wide distribution of local switching fields. This behavior is characteristic of an under-annealed regime for room-temperature-sputtered YIG. Amorphous or weakly ordered YIG precursors generally require high-temperature post-annealing to develop crystalline garnet order [3,38], and reactive-sputtered Y-Fe-O films on GGG have shown clear YIG/GGG reflections only after annealing above about 800 °C [39]. The 650 °C film is therefore interpreted as a low-temperature recrystallization state in which residual disorder, incomplete garnet formation and spatially nonuniform local anisotropy create a strong pinning landscape.

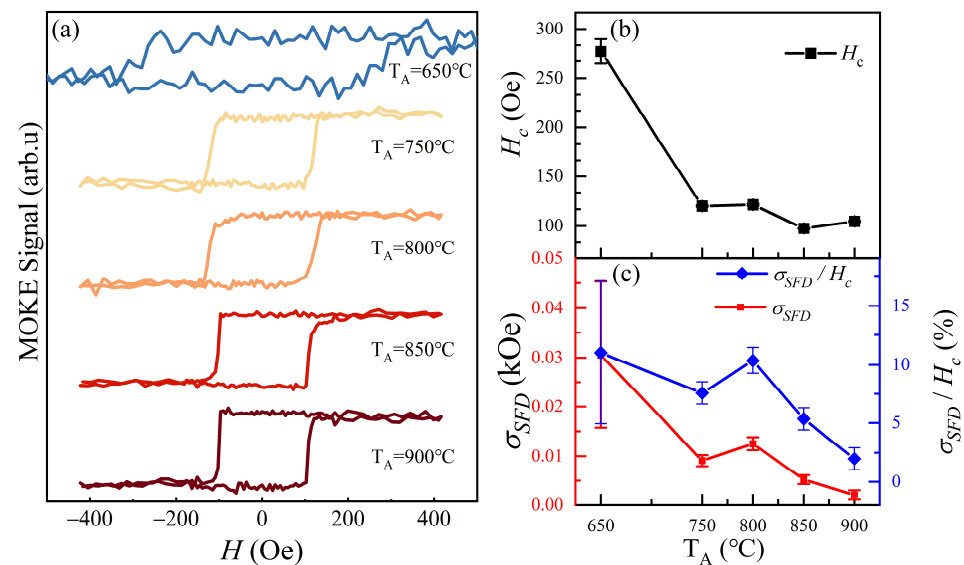


Figure 2. Annealing temperature dependence for 48 nm YIG/GGG films: (a) longitudinal Kerr loops; (b) coercive field H_c ; and (c) switching-field standard deviation σ_{SFD} and normalized switching-field distribution σ_{SFD}/H_c .

Figure 2b shows that H_c decreases from 277.06 ± 12.63 Oe at 650°C to 119.76 ± 0.80 Oe at 750°C and 121.05 ± 0.92 Oe at 800°C . It reaches 97.42 ± 0.60 Oe at 850°C and then changes to 104.56 ± 0.72 Oe at 900°C . The 650°C coercive field is therefore more than twice the values obtained after annealing at 750 – 900°C . Such a sharp reduction is consistent with thermal removal of defect-controlled pinning and homogenization of the magnetic free-energy landscape. In sputtered YIG, off-stoichiometry, density variations and defects are known to alter M_s , H_c , magneto-optical response and microwave linewidth [32,42], while defects, roughness and local variations in magnetic parameters can trap domain walls during reversal [53]. The large error bar of H_c at 650°C is also physically meaningful: the broad loop transition gives a wider set of statistically acceptable switching centers, rather than a sharply defined reversal field.

Figure 2c resolves the annealing dependence of the reversal-field distribution. The fitted σ_{SFD} values are 0.03051 ± 0.01478 , 0.00907 ± 0.00114 , 0.01254 ± 0.00131 , 0.00521 ± 0.00091 and 0.00207 ± 0.00098 kOe at 650 , 750 , 800 , 850 and 900°C , respectively. The corresponding σ_{SFD}/H_c values are $11.01 \pm 6.08\%$, $7.57 \pm 0.96\%$, $10.36 \pm 1.08\%$, $5.35 \pm 0.94\%$ and $1.98 \pm 0.95\%$. Compared with the 850°C film, the 650°C film has an approximately six-fold larger σ_{SFD} and a more than two-fold larger normalized distribution. This means that the low-temperature film is not only harder to switch but also less uniform in its field-driven reversal. The large σ_{SFD} uncertainty at 650°C follows the same logic as the H_c uncertainty: a sloped, spatially distributed transition allows several similar Gaussian-width solutions during residual-bootstrap refitting.

The decrease in σ_{SFD}/H_c from 650 to 850 – 900°C is consistent with a transition from defect-dominated reversal to more synchronized domain nucleation and domain-wall propagation. Sputtered YIG studies have shown that annealing-dependent crystallinity, surface morphology and magnetic inhomogeneity strongly affect linewidth and magnetic response [40,41], and domain-wall studies show that local pinning sites broaden and randomize wall motion [53,54]. This framework also explains why 850 and 900°C should not be described by a single “best” label. The 850°C film gives the lowest H_c and a much narrower σ_{SFD}/H_c than the under-annealed films, so it is the most favorable condition for low-field switching. The 900°C film gives the smallest fitted σ_{SFD}/H_c , so it is the best condition for the static switching uniformity metric. The broader process window is

therefore 850–900 °C: 850 °C favors easy reversal, whereas 900 °C favors the narrowest quasistatic switching distribution.

The dynamic response was evaluated using multi-frequency field-swept FMR. Figure 3a shows representative traces for the 48 nm film annealed at 850 °C. Each positive–negative line pair is the field derivative of the microwave absorption signal recorded by lock-in detection. A single derivative Lorentzian was used consistently to obtain the resonance field and effective linewidth at each frequency.

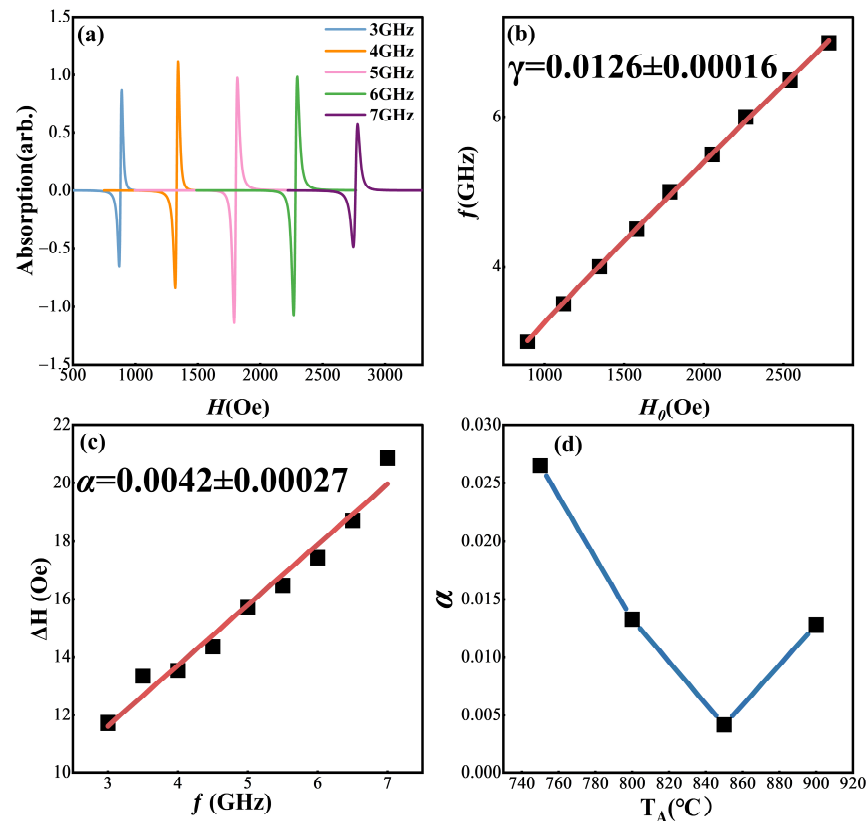


Figure 3. FMR analysis of the 48 nm YIG/GGG film annealed at 850 °C: (a) field derivative of microwave absorption in arbitrary units from 3 to 7 GHz; (b) frequency f versus resonance field H_0 , fitted with the in-plane Kittel relation; (c) effective linewidth ΔH versus f , fitted linearly to obtain $\alpha = (4.2 \pm 0.27) \times 10^{-3}$; and (d) effective damping α versus annealing temperature. The uncertainty in α is obtained from the linear linewidth fit.

The resonance field was mapped as a function of microwave frequency f (Figure 3b) and analyzed using the Kittel relation [55]:

$$f = \gamma/2\pi \sqrt{H_0(H_0 + 4\pi M_{\text{eff}})} \quad (1)$$

where $\gamma/2\pi = 2.01 \text{ GHz kOe}^{-1}$ is the fitted gyromagnetic ratio and $4\pi M_{\text{eff}} = 1.537 \text{ kOe}$ is the effective magnetization obtained from the Kittel fit. The red line in Figure 3b follows the measured 3–7 GHz dispersion. The effective linewidth was then analyzed using Equation (2), where ΔH_0 represents the frequency-independent inhomogeneous contribution.

$$\Delta H = 4\pi\alpha f/\gamma + \Delta H_0 \quad (2)$$

The linear fit in Figure 3c gives $\alpha = (4.2 \pm 0.27) \times 10^{-3}$ for the 850 °C film. Figure 3d shows that α decreases from 750 to 850 °C and then increases at 900 °C. The minimum in α therefore occurs at 850 °C, even though the smallest fitted σ_{SFD}/H_c occurs at 900 °C.

This separation is important: the condition that gives the narrowest quasistatic switching distribution does not necessarily minimize the resonant loss measured by FMR.

The non-monotonic α trend can be understood as a balance between improved garnet recrystallization and the dynamic loss channels introduced or amplified by further thermal treatment. Below the optimum, incomplete ordering, defect-controlled anisotropy and magnetic inhomogeneity can broaden the resonance. Near 850 °C, these contributions are reduced, giving the lowest measured α . At 900 °C, the static reversal distribution continues to narrow, but the FMR damping increases, indicating that quasistatic switching uniformity and microwave dissipation are controlled by overlapping but nonidentical microstructural factors. Interface-related relaxation, two-magnon scattering, strain or anisotropy inhomogeneity and surface-associated magnon scattering are established contributors to thin-film YIG linewidths [19,40,56–59], while sputtered YIG studies also show that stoichiometry and density affect microwave properties [32,42]. The 850 °C film therefore provides the strongest overall balance in the temperature series because it combines the clearest film-associated XRD shoulder, the lowest H_c , a substantially reduced σ_{SFD}/H_c and the lowest α .

3.3. Influence of Film Thickness

Figure 4a compares the Kerr loops of the thickness series annealed at 850 °C. Quantitative loops were resolved for films from 35 to 120 nm, while the 20 nm signal remained below the practical detection threshold of the setup. The signal-to-noise ratio (SNR) describes the separation between the positive and negative saturation levels relative to their noise, and is calculated using Equation (3). The absence of a reliable 20 nm loop should therefore be interpreted as a detection threshold result for the present optical setup, not as evidence that the film is nonmagnetic. At this thickness, the magneto-optically active volume is small, and the Kerr contrast competes with substrate reflection, thin-film interference background and instrumental noise.

$$\text{SNR} = 20\log_{10}\left(|\mu_+ - \mu_-|/\sqrt{\sigma_+^2 + \sigma_-^2}\right) \quad (3)$$

where μ_+ and σ_+ are the mean and standard deviation of the positive-saturation data over $0.85 H_{\text{max}} \leq H \leq H_{\text{max}}$, and μ_- and σ_- are the corresponding quantities over $H_{\text{min}} \leq H \leq 0.85 H_{\text{min}}$.

The Kerr signal strengthens from the ultrathin limit, and the 75 nm film reaches the highest SNR of 11.83 dB within the series. This threshold-like evolution is not assigned to crystalline quality alone. It is more consistently understood as the combined result of increasing magnetic volume, thickness-dependent magneto-optical conversion, optical interference in the film/substrate stack and the decreasing relative weight of interface-associated disorder or strain [19,57,60,61]. At intermediate thickness, the film provides sufficient Kerr contrast while retaining a compact reversal distribution; this balance explains why the SNR maximum and the narrowest switching distribution both occur near 75 nm in the present series. The well-resolved loops from 35 to 120 nm enable a direct comparison of their switching fields and reversal distributions.

Figure 4b shows a non-monotonic thickness dependence of H_c . The fitted values are 119.22 ± 0.81 Oe at 35 nm, 97.42 ± 0.59 Oe at 48 nm, 90.27 ± 0.35 Oe at 75 nm, 106.12 ± 0.28 Oe at 90 nm and 89.25 ± 0.49 Oe at 120 nm. The decrease toward 75 nm, followed by the variations at 90 and 120 nm, highlights an intermediate-thickness regime with particularly favorable low-field reversal.

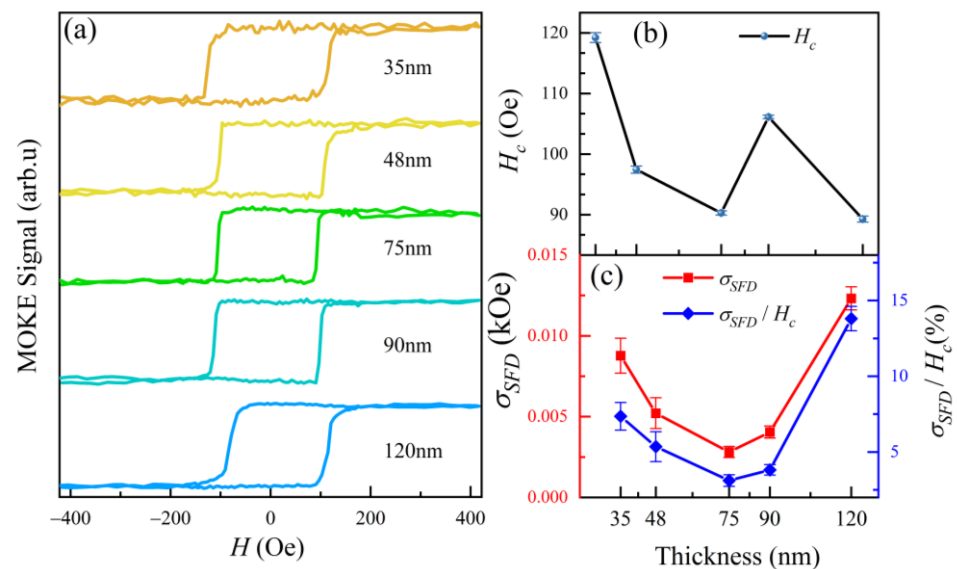


Figure 4. Thickness dependence for YIG/GGG films annealed at 850 °C: (a) longitudinal Kerr loops; (b) coercive field H_c ; and (c) switching-field standard deviation σ_{SFD} and normalized distribution σ_{SFD}/H_c .

The fitted switching-width metrics show a clearer minimum at intermediate thickness. σ_{SFD} is 0.00877 ± 0.00108 , 0.00521 ± 0.00096 , 0.00281 ± 0.00035 , 0.00405 ± 0.00037 and 0.01232 ± 0.00071 kOe for 35, 48, 75, 90 and 120 nm, respectively. The corresponding σ_{SFD}/H_c values are $7.36 \pm 0.91\%$, $5.35 \pm 0.99\%$, $3.11 \pm 0.38\%$, $3.81 \pm 0.35\%$ and $13.80 \pm 0.80\%$. Thus, 75 nm gives the narrowest fitted reversal distribution, while the 120 nm sample shows the broadest normalized distribution.

The combined H_c and σ_{SFD}/H_c trends point to competing interface, strain relaxation, morphology and reversal-pathway contributions. The decrease in H_c from 35 to 75 nm can be understood as the diminishing relative importance of interface-controlled pinning and ultrathin-film magnetic inhomogeneity as the magnetic volume increases. The subsequent changes at 90 and 120 nm show that thickness does not simply remove defects monotonically; additional strain relaxation, surface morphology changes or multiple nucleation and wall-propagation pathways can broaden the reversal landscape at larger thickness. Related non-monotonic linewidth behavior has been reported in sputtered YIG [40], and thickness-dependent strain and damping have been observed in LPE YIG [61]. Similar process–property coupling in sputtered magnetic films [62] and tunable anisotropy in sputtered epitaxial YIG [63] further support this interpretation. The 120 nm film is particularly instructive: although its H_c is low, its σ_{SFD}/H_c rises to $13.80 \pm 0.80\%$, indicating that low average coercivity does not guarantee a narrow or spatially uniform switching distribution. This progression explains why the optimum emerges at an intermediate thickness rather than at either end of the measured range.

The SEM observations provide direct morphological context for two conditions central to the process–property comparison. In particular, the 75 nm film annealed at 850 °C, which gives the best combined switching distribution and damping metrics in the thickness series, retains a laterally continuous, comparatively feature-poor background at high magnification (Figure 1e). The low-magnification overview shows that particulates are spatially isolated rather than densely distributed (Figure 1d). This morphology is consistent with the stable magneto-optical and resonant response of the intermediate-thickness film.

Figure 5a shows the field-derivative FMR traces of the 75 nm film. The resonance shifts to a higher field with increasing frequency. Analysis of the resonance field dispersion gives $\gamma/2\pi = 1.96 \text{ GHz kOe}^{-1}$, and the linewidth–frequency fit gives $\alpha = (5.84 \pm 0.16) \times 10^{-3}$.

Figure 5b summarizes the fitted α values and their regression uncertainties across the thickness series. Because all thickness samples were analyzed over the same 3–7 GHz interval with the same linewidth convention, the slope-derived α values provide a controlled comparison of effective dynamic loss within this sample set.

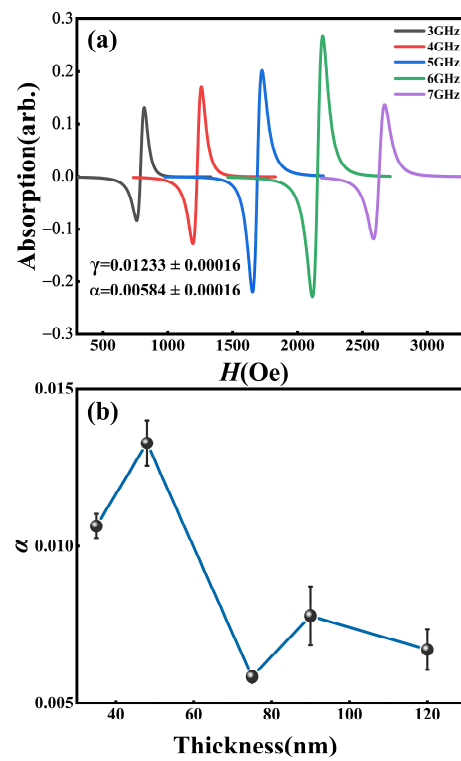


Figure 5. Thickness-dependent FMR: (a) field derivative of microwave absorption for the 75 nm film annealed at 850 °C, measured from 3 to 7 GHz; (b) effective damping α versus YIG thickness. Symbols in (b) are the slope-derived effective α values obtained from the linewidth–frequency fits, and vertical bars are regression uncertainties.

The effective damping is also non-monotonic with thickness. It is comparatively high for the 35 and 48 nm films, reaches the minimum measured value at 75 nm and remains below the thin-film values at 90 and 120 nm. This trend should not be read as a direct plot of intrinsic Gilbert damping alone. The fitted slope can contain intrinsic damping together with extrinsic slope-like contributions caused by two-magnon scattering, interface-related relaxation and magnetic inhomogeneity. The 75 nm film therefore combines the smallest σ_{SFD}/H_c with the lowest effective α , providing the best balance of switching uniformity and dynamic loss within the thickness series.

The higher effective damping of the thinner films is consistent with a larger relative interface contribution and enhanced inhomogeneous broadening. In thin magnetic films, roughness, interface disorder and spatial variations in anisotropy can activate two-magnon and other extrinsic relaxation channels, whereas the frequency-independent part of the linewidth fit is represented by ΔH_0 . The present 3–7 GHz field-swept data are sufficient for comparing effective α under a common protocol. A full microscopic decomposition is usually made using angle-dependent or wider-frequency FMR, so the present discussion assigns the thickness trend to effective damping while identifying intrinsic Gilbert damping, two-magnon scattering and other inhomogeneous contributions as distinct possible channels [19,40,56–59,64]. At 120 nm, σ_{SFD}/H_c rises while α remains comparatively low, showing that reversal uniformity and resonant loss respond differently to thickness. Selection based only on α would favor several thicker films but would miss the substantial switching broadening at 120 nm. The paired analysis instead identifies 75 nm as the

condition that preserves both a compact switching distribution and the lowest measured effective dynamic loss.

3.4. Quantitative Literature Benchmarking

Table 1 compares the present values with representative YIG films produced by RF sputtering, room-temperature deposition followed by recrystallization, PLD, LPE and mist CVD. Optimized sputtered, PLD and LPE films reach α values in the 10^{-5} – 10^{-4} range [3,27,34,41], establishing the broader performance scale for low-loss YIG. The present study adds a paired assessment of switching-field statistics and multi-frequency FMR damping across controlled temperature and thickness series.

Table 1. Quantitative comparison of representative YIG thin-film growth routes. Values follow the linewidth and damping conventions reported by each source; a dash indicates that the corresponding metric was not provided.

Growth Route and Study	Film/Substrate	Post-Growth Condition	Reported FMR Metric	Static or Switching Metric	Relevance to the Present Work
RF sputtering, present work	48 and 75 nm YIG/GGG(111)	O ₂ , 850 °C, 2 h	$\alpha = (4.2 \pm 0.27) \times 10^{-3}$ for 48 nm; $\alpha = (5.84 \pm 0.16) \times 10^{-3}$ for 75 nm	$\sigma_{\text{SFD}}/H_c = 5.35 \pm 0.94\%$ for 48 nm and $3.11 \pm 0.38\%$ for 75 nm	Paired Kerr-switching and FMR metrics from the same controlled sample series
RF sputtering, Ding et al. [41]	75 nm YIG/GGG(111)	O ₂ anneal at 900 °C	$\alpha \approx 5.2 \times 10^{-5}$	$H_c \approx 0.18$ Oe	Low-damping sputtered YIG benchmark
RF sputtering, Cao Van et al. [40]	20–100 nm YIG/GGG(111)	Optimum near 875 °C	Minimum $\Delta H_{\text{pp}} = 1.9$ Oe at 9.43 GHz for 60 nm	H_c and M_s reported	Sputtered YIG benchmark for non-monotonic thickness response
Room-temperature deposition and recrystallization, Hauser et al. [3]	20 and 56 nm YIG/GGG(111)	O ₂ , 800–900 °C	$\alpha = (7.39 \pm 1.40) \times 10^{-5}$ for 20 nm and $(6.15 \pm 1.50) \times 10^{-5}$ for 56 nm	As-deposited films were amorphous	Post-deposition crystallization benchmark
PLD, Onbasli et al. [27]	17–200 nm YIG/GGG	Elevated-temperature growth and rapid thermal annealing	Minimum $\alpha = 2.2 \times 10^{-4}$	$H_c < 2$ Oe	Low-damping PLD benchmark
LPE, Dubs et al. [34]	11–42 nm YIG/GGG(111)	Liquid-phase epitaxy	$\alpha \leq 1.3 \times 10^{-4}$ for films ≥ 21 nm	—	Low-damping LPE benchmark
Mist CVD, Yao et al. [23]	YIG thin films on oxide substrates	Chemical deposition and heat treatment	—	Magneto-optical response reported	Magneto-optical chemical-deposition benchmark
PLD, Zaki et al. [36]	YIG/GGG and YIG/YAG	Substrate at 500 °C; oxygen pressure and air anneal optimized	—	Magnetization = 143 emu cm ⁻³ ; coercive field ≈ 1 Oe	PLD benchmark for bulk-like magnetization and low coercivity

Most benchmark studies emphasize linewidth, damping, magnetization or structural quality. By reporting both σ_{SFD}/H_c and α , the present series connects quasistatic switching uniformity with dynamic loss. This paired view provides an additional engineering criterion for selecting film-processing conditions. It also reveals information that a single performance metric cannot capture. The temperature series separates the annealing condition for minimum damping from that for the narrowest fitted reversal distribution, while the thickness series identifies one condition that minimizes both. This comparison converts the measured trends into a practical selection map for magneto-optical switching and microwave-resonance experiments.

The 850 °C/75 nm condition also lies within a recurring process regime for sputtered YIG. Ding et al. obtained $\alpha \approx 5.2 \times 10^{-5}$ for a 75 nm film after 900 °C annealing [41], while Cao Van et al. reported a minimum peak-to-peak linewidth of 1.9 Oe for a 60 nm film annealed

near 875 °C [40]. These studies support high-temperature oxygen treatment and thicknesses of several tens of nanometers as practical starting points for low-loss sputtered YIG.

For experiments requiring both reproducible field reversal and low microwave loss, H_c , σ_{SFD}/H_c and α provide complementary selection criteria. In the temperature series, 900 °C yields the smallest fitted normalized switching width, whereas 850 °C yields the lowest α . In the thickness series annealed at 850 °C, the 75 nm film minimizes both quantities. The process–property map therefore separates a temperature-dependent trade-off from a clear intermediate-thickness optimum.

Future work combining nanoscale topography, cross-sectional interface imaging, composition and stress-sensitive measurements with wider-frequency and angle-dependent FMR can connect this empirical process map more directly to its microscopic origins. Such correlations can further refine the simultaneous control of switching uniformity and microwave loss.

4. Conclusions

By combining XRD, SEM, longitudinal MOKE and multi-frequency field-swept FMR, this study establishes an annealing- and thickness-dependent process–property map for RF-sputtered YIG/GGG films. The clearer YIG(444)-region shoulder at 850 °C accompanies a pronounced improvement in magnetic response. Representative SEM images of the 48 nm/800 °C and 75 nm/850 °C films show laterally continuous surface backgrounds with sparse localized particulates. H_c decreases from 277.06 ± 12.63 Oe at 650 °C to 97.42 ± 0.60 Oe at 850 °C, where α reaches its minimum of $(4.2 \pm 0.27) \times 10^{-3}$. The 900 °C film gives the smallest fitted σ_{SFD}/H_c of $1.98 \pm 0.95\%$. The temperature series therefore distinguishes the annealing condition for minimum dynamic loss from that for the narrowest switching-field distribution.

The thickness series identifies a clearer combined optimum. At 75 nm, the Kerr loop SNR reaches 11.83 dB, σ_{SFD}/H_c decreases to $3.11 \pm 0.38\%$ and α reaches $(5.84 \pm 0.16) \times 10^{-3}$. Increasing the thickness to 120 nm raises σ_{SFD}/H_c to $13.80 \pm 0.80\%$, even though the dynamic loss remains comparatively low. The intermediate 75 nm thickness therefore provides the most balanced quasistatic and dynamic response within the investigated series.

Taken together, the results show that coercivity, switching-field distribution and effective damping provide complementary criteria for process selection. The paired MOKE–FMR analysis identifies 850 °C and 75 nm as the most effective combination for balancing switching uniformity and resonant loss in this sample set. The comparison with established sputtered, PLD, LPE and chemical-deposition routes further places this processing choice within the broader YIG thin-film landscape. This process–property framework provides a practical basis for selecting RF-sputtered YIG films for magneto-optical switching, microwave characterization and related magnonic experiments.

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