

Supplementary Pages :

For “Spin-to-Charge conversion for ultra-thin Mn₃Al/W capping layers on PLD grown YIG”

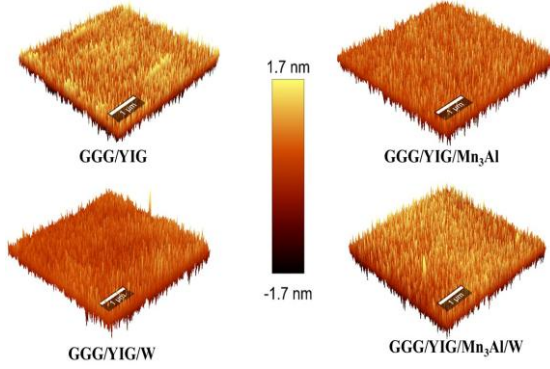


Figure 1: AFM topographic images for RMS roughness.

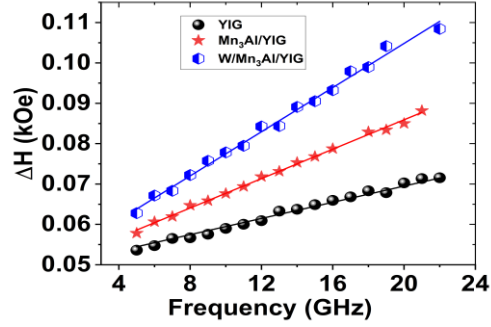


Figure 2: FMR Linewidths versus frequencies. Derivation of Gilbert damping for three PLD grown structures

Thin films of Yttrium Iron Garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) were deposited on single-crystalline GGG substrates using pulsed laser deposition (PLD) technique in an ultra-high vacuum system at a base pressure of less than 8×10^{-7} mbar. Deposition was carried out with the help of an excimer laser operated at 248 nm, 20 ns, 10 Hz and 300 mJ as the ablation source from a YIG target. The thickness of the CFS films (t_{CFS}) was controlled by varying the number of laser shots.

X-ray diffraction (XRD) in the θ – 2θ configuration using Cu-K α radiation showed deposited films as single crystallinity over GGG(111) substrate. Using atomic force microscopy (AFM), rms roughness was extracted from the topographic images of all the samples and was found to be less than 0.6 nm (Fig:1 & Table below). Low rms roughness indicates that all the films exhibit a smooth and continuous surface. The saturation magnetization of YIG films was found to be near the bulk value of YIG. The coercivity remains almost constant around 12 Oe for all samples. The YIG films show excellent soft magnetic nature due to low coercivity values.

Sample	RMS roughness (ρ_{rms})	Skewness	kurtosis
GGG/YIG	0.63283	0.02819	3.9833
GGG/YIG/W	0.32819	0.00943	3.6829
GGG/YIG/Mn ₃ Al	0.40193	0.06633	4.1051
GGG/YIG/Mn ₃ Al/W	0.53921	0.09641	4.1720

Dynamic magnetic properties were studied by using a broadband (4 – 24 GHz) ferromagnetic resonance (FMR) spectroscopy with a two-port vector network analyzer (VNA, Keysight, USA), connected to a "S"-shaped coplanar waveguide (CPW). Samples were flipped upside down on the signal line of the CPW for a flip-chip configuration which ensured that the DC magnetic field was orthogonal to the RF magnetic field (h_{RF}). FMR has been successfully used to study the magnetization dynamics of YIG (FM) and heterostructure films. The values of resonance field positions (H_r) and resonance linewidths (ΔH) were obtained from the FMR spectra using a symmetric and asymmetric Lorentzian line-shape function as below;

$$S_{21} = -S \frac{\left(\frac{\Delta H}{2}\right)^2 (H_{ext} - H_r)}{\left(\left(\frac{\Delta H}{2}\right)^2 + (H_{ext} - H_r)^2\right)} + A \frac{\left(\frac{\Delta H}{2}\right) \left(\left(\frac{\Delta H}{2}\right)^2 (H_{ext} - H_r)^2\right)}{\left(\left(\frac{\Delta H}{2}\right)^2 + (H_{ext} - H_r)^2\right)^2} .$$

The Landau–Lifshitz–Gilbert (LLG) method was utilized to evaluate the time-dependent magnetization as given below;

$$f = \frac{\gamma \mu_0}{2\pi} \sqrt{(H_{FMR} + H_K)(H_{FMR} + M_{eff} + H_K)} .$$

Sample	H_{eff} (kOe)	H_K (kOe)	ΔH_0 (kOe)	α & α_{eff}
YIG	1.87	0.13	0.04944	0.0015
Mn₃Al/YIG	2.03	0.12	0.04949	0.0027
W/Mn₃Al/YIG	2.29	0.03	0.05013	0.0041

Compared with the bare YIG film, the heterostructures exhibit a systematically larger linewidth, (with no enhancement of zero-frequency linewidth; ΔH_0) suggesting an additional interfacial relaxation channel which may be associated with spin angular momentum transfer across the Mn₃Al/W interface. The fitting (Fig.2) clearly shows a linear response in ΔH versus f . This suggests that the contribution of two-magnon scattering (TMS) in the heterostructures are almost zero (TMS corresponds to a highly nonlinear behavior). The damping constant obtained from the fitting are termed as the effective damping constant (α_{eff}) for the two heterostructures. The α_{eff} and ΔH_0 values obtained from fitting;

$$\mu_0 \Delta H = \mu_0 \Delta H_0 + \frac{4\pi \alpha_{eff} \hbar}{g \mu_B} f .$$

The main results correspond to spin-to-charge conversion due to spin-pumping phenomenon are shown in table above, where α_{eff} and ΔH_0 are tabulated for different heterostructures. The effective spin-mixing conductance ($g_{eff}^{\uparrow\downarrow}$) exhibit relatively large value indicating efficient transfer of spin angular momentum across the YIG/ Mn₃Al/W interface during ferromagnetic resonance, resulting in enhanced magnetization relaxation through spin pumping.