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Enhanced ferromagnetic resonance linewidth of the free layer in perpendicular magnetic tunnel junctions

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We report the frequency dependence of the ferromagnetic resonance linewidth of the free layer in magnetic tunnel junctions with all perpendicular–to–the–plane magnetized layers. While the magnetic–field–swept linewidth nominally shows a linear growth with frequency in agreement with Gilbert damping, an additional frequency–dependent linewidth broadening occurs that shows a strong asymmetry between the absorption spectra for increasing and decreasing external magnetic field. Inhomogeneous magnetic fields produced during reversal of the reference and pinned layer complex is demonstrated to be at the origin of the symmetry breaking and the linewidth enhancement. Consequentially, this linewidth enhancement provides indirect information on the magnetic coercivity of the reference and pinned layers. These results have important implications for the characterization of perpendicular magnetized magnetic random access memory bit cells. [http://dx.doi.org/10.1063/1.4977969]

Spin-transfer-torque magnetic random access memory (STT-MRAM) based on perpendicular magnetic tunnel junctions (pMTJs) shows potential as both a discrete memory replacement and a fast, dense embedded memory.[1,2] However, gains in spin-torque switching efficiency are needed in order to realize higher density MRAM arrays compatible with current CMOS node sizes. These gains can be achieved through materials optimization of the free layer (FL) to exhibit higher retention thermal stability and lower Gilbert damping.

Broadband ferromagnetic resonance (FMR) spectroscopy can be used to guide optimization of thermal stability and damping through evaluation of the frequency dependence of the resonance field and the linewidth. Due to the distinct resonance features (anisotropy, damping) of the various layers in a typical pMTJ, it is possible to measure the material properties of each individual layer - free layer (FL) and synthetic antiferromagnetic layers including pinned layer (PL) and reference layer (RL) - within its film stack instead of as an isolated, single layer magnetic film. This operating environment presents unique possibilities to measure both the individual layer properties and the interaction strengths between the exchange coupled RL and PL.[3,4] It can also present unique resonance absorption characteristics due to the magnetostatic fields between the FL and the PL(RL). As depicted in Fig. 1, the relative anti–parallel magnetization alignment of the PL and RL is induced through antiferromagnetic interactions to provide a nearly zero stray field acting on the free layer magnetization.[5] However, the coupled PL and RL could create extra spatially inhomogeneous stray fields acting on the FL when either of those layers is no longer uniformly magnetized. This inhomogeneous field can add inhomogeneous linewidth broadening to the FMR absorption linewidth of the FL.

Here, we present broadband ferromagnetic resonance (FMR) spectroscopy of CoFeB-based free layers (FLs) integrated into full-film pMTJ stacks. The pMTJ is a bottom-pinned stack consisting

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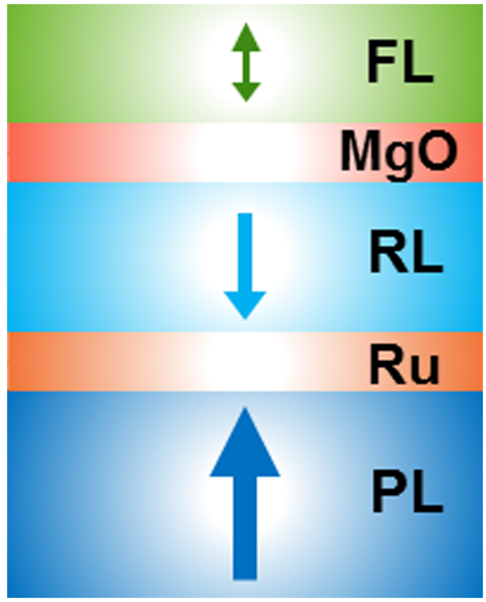

FIG. 1. Schematic of a pMTJ stack, including FL and the antiferromagnetic coupled PL and RL.

of a [Co/Pt]-based pinned layer (PL), coupled to a CoFeB-based reference layer (RL). The free layer is a composite CoFeB layer in which an ultrathin Ta layer has been inserted between two thin CoFeB layers to enhance the thermal stability. The FL shows low Gilbert damping and high perpendicular magnetic anisotropy, a consequence of the optimization of the free layer composition. We also present experimental evidence of linewidth enhancement for field–swept FMR at frequencies whose resonance fields approach the switching fields of the PL and RL, a potential artefact for FL damping estimates in pMTJs. While similar behavior has been reported on the free layer linewidth of in–plane magnetized MTJs, this work provides evidence for this effect in MTJs with all layers magnetized perpendicular to the plane.[6] A magnetostatic coupling model that takes into account inhomogeneous fields produced during reversal of the PL and RL layers explains the observed linewidth enhancement.

The Kittel equation for ferromagnetic resonance governs the relationship between microwave excitation frequency and resonant applied magnetic field for fields applied normal to the thin film plane:

$$\left(\frac{\omega}{\gamma}\right) = \mu_0 \left(H_{\mathrm{res}} + H_{\mathrm{eff}}\right), \tag{1}$$

where $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, g is the g-factor, μ_B is the Bohr magneton, $\hbar$ is the reduced Planck constant, μ_0 is the vacuum permeability and $H_{\mathrm{eff}} = 2K_1/M_S - M_S$ is the effective perpendicular anisotropy (comprising the uniaxial anisotropy and the saturation magnetization). In Fig. 2, we present a series of out–of–plane field swept absorption spectra at frequencies between 14 GHz and 50 GHz for the free layer of the pMTJ film. The ferromagnetic resonance field and linewidth are obtained by fitting the absorption data to the sum of symmetric and asymmetric derivative Lorentzian lineshapes, enabling the determination of the resonance field and the linewidth at each frequency.

Figure 3 shows the frequency–dependence of the ferromagnetic resonance field and the linewidth. Applying the Kittel relation from Eq. 1, we obtain a best-fit curve to the resonance field versus frequency data in Fig. 3(a), from which we use an asymptotic frequency analysis method to estimate $\mu_0 H_{\mathrm{eff}} = 0.349\ \mathrm{T} \pm 0.003\ \mathrm{T}$ and $g = 2.180 \pm 0.004$.[7] Uncertainty in the best–fit parameters comprises the standard uncertainty from a least–squares fit to Eq. 1 and the uncertainty in the precision of the measured field values. Finally, we arrive at a positive value for H_{eff} that agrees with the observed perpendicular magnetization of the FL in this film.

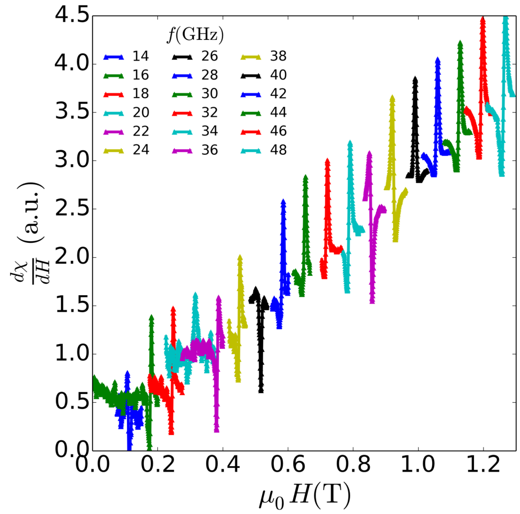

FIG. 2. Representative derivative microwave absorption signal ($d\chi/dH$) versus applied out–of–plane magnetic field $\mu_0 H$ for *rf* excitation frequencies between 14 GHz and 49 GHz (solid triangle markers). Best-fit lines (solid lines) to the lineshapes reflect a combination of symmetric and asymmetric derivative Lorentzians. Vertical offsets were added to better visually distinguish between spectral lines and reflect a linear in frequency additive shift.

The linewidth versus frequency for fields applied out–of–plane is expected to have the following linear relationship:[8]

$$\Delta H = \frac{4\pi\alpha f}{\gamma\mu_0} + \Delta H_0, \tag{2}$$

where α is the unitless Gilbert damping parameter and ΔH_0 is a frequency–independent factor attributed to inhomogeneous linewidth broadening. Despite the apparent deviation from the linear

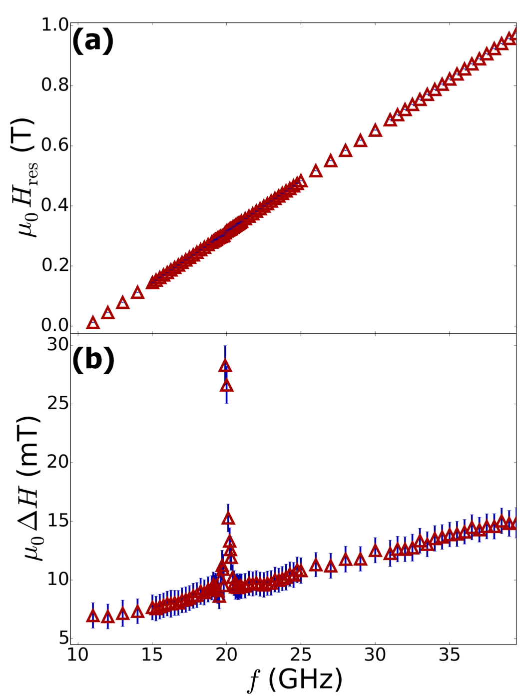

FIG. 3. (a) Out–of–plane resonance field versus ferromagnetic resonance absorption frequency and (b) Linewidth versus ferromagnetic resonance absorption frequency.

linewidth versus frequency trend in the vicinity of $f = 20$ GHz, it is possible to mask the points in this region and obtain a satisfactory linear fit to the data. From the best=-fit line to our linewidth versus frequency data, we extracted a Gilbert damping factor $\alpha = 0.0043 \pm 0.0002$ and an inhomogeneous broadening of $\Delta H_0 = 3.6\ \mathrm{mT} \pm 0.5\ \mathrm{mT}$. The particularly low value for the damping in the CoFeB free layer is attributed to the presence of non–conducting MgO layers on both sides of this layer.[9,10]

The presence and magnitude of the deviations in the linewidth from its linear trend depends strongly on the magnetic history of the film. Figure 4 reveals the asymmetric location of the peak linewidth for field increasing and decreasing. The film was reset using a large negative (positive) field before performing a field increasing (decreasing) scan. For FMR scans under increasing fields, the linewidth exhibits a local maximum around 20 GHz. On the other hand, FMR scans under decreasing fields exhibit a local linewidth maximum at a lower frequency (17 GHz).

The origin of the sharp maxima in the linewidth dependence on frequency and the corresponding asymmetry with respect to the direction of scanned out–of–plane field can be understood from magnetostatic interactions between the free layer and the pinned reference complex. Figure 5 shows the magnetization versus applied out–of–plane magnetic field hysteresis loop for the pMTJ film. Increasing the field from negative saturation, in which the pinned layer, reference layer and free layer are all magnetized "down", the RL reverses from "down" to "up" at approximately −200 mT, the FL reverses at fields below 5 mT, and the PL is switched at approximately +300 mT. This remagnetization process is reversed as the field is decreased from positive saturation back through negative saturation.

For applied fields in the vicinity of the coercive field of RL(PL), the otherwise uniformly magnetized layers comprising the synthetic antiferromagnet breaks up into multiple domains, leading to the generation of spatially inhomogeneous magnetostatic fields that can modulate the otherwise uniform magnetostatic fields interacting with the free layer magnetization. This spatially inhomogeneous dipolar coupling between the layers has been shown to break the lateral symmetry between layers in perpendicularly magnetized spin–transfer devices.[11,12] For continuous pMTJ films, the strength and characteristic length scale of lateral variation in the magnetostatic field interaction strength within the free layer will depend on the distribution of magnetic domains in the layer (RL, PL) undergoing reversal. A recent mean–field model predicts increases in the inhomogeneous linewidth broadening proportional to the field strength due to lateral inhomogeneities.[13] This behavior agrees well with the observed doubling of the intensity of the linewidth peak at 20 GHz compared to the peak at 17 GHz shown in Fig. 4. We attribute this asymmetry to the larger magnetization change at 300 mT compared to the smaller magnetization change at 200 mT and the associated larger magnetostatic field.

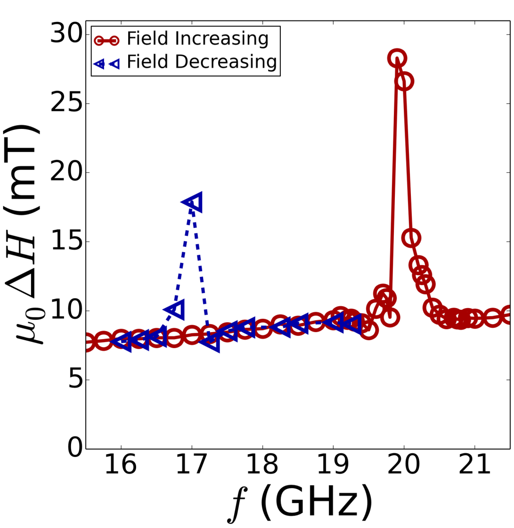

FIG. 4. Asymmetric linewidth versus frequency trends for increasing (open red circles) and decreasing (open blue triangles) applied out–of–plane magnetic fields.

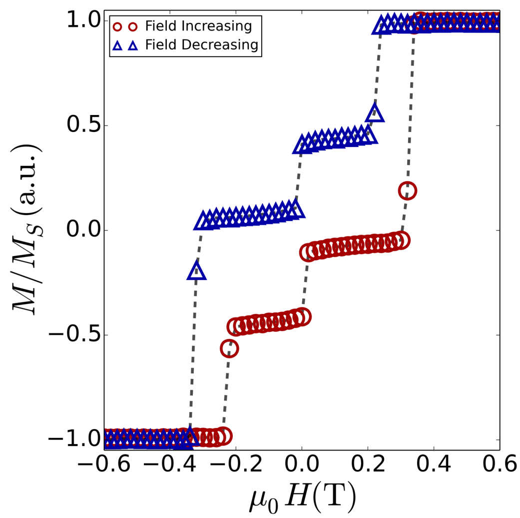

FIG. 5. Magnetization versus applied out–of–plane field for perpendicular magnetic tunnel junction film.

We can use the local peak in the linewidth versus frequency trend to estimate the coercive field of the RL(PL). For increasing field, we find a peak in the linewidth at $f = 19.90$ GHz ± 0.05 GHz, corresponding to a resonance field $\mu_0 H_r = 0.311$ T ± 0.004 T. This agrees well with the estimated coercive field for the PL from Fig. 4 (0.32 T ± 0.01 T). And for decreasing field, the peak linewidth at $f = 17.0$ GHz ± 0.1 GHz corresponds to a resonance field $\mu_0 H_r = 0.211$ T ± 0.006 T, also in good agreement with the RL transition estimated from magnetometry (0.22 T ± 0.01 T).

In conclusion, we investigated the ferromagnetic resonance linewidth of the free layer of an all–perpendicular magnetic tunnel junction film. We observed linewidth enhancement of nearly three times due to the inhomogeneous fields produced by the reference and pinned layers of the pMTJ during remagnetization, which led to an asymmetry in the frequency position of the linewidth peak depending on the direction of swept field FMR measurements. The peak locations were shown to correspond directly to the remagnetization fields of the layers, as checked by vibrating sample magnetometry, which enables one to use the linewidth measurements of the free layer of pMTJs to identify the reversal fields of the complementary layers. These findings are an important step for gaining a better understanding of inhomogeneity–induced spin dynamics and relaxation in pMTJs.

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[1] Y. Huai, J. Zhang, Y. Zhou, X. Wang, E. Abedifard, Z. Wang, X. Hao, D. Jung, K. Satoh, H. Gan *et al.*, in *2015 IEEE Magnetics Conference (INTERMAG)* (2015), pp. 1–1, ISSN 2150-4598.
[2] A. D. Kent and D. C. Worledge, Nat Nano **10**, 187 (2015).
[3] T. Devolder, S. Couet, J. Swerts, and A. Furnemont, Applied Physics Letters **108**, 172409 (2016).
[4] L. Fallarino, V. Sluka, B. Kardasz, M. Pinarbasi, A. Berger, and A. D. Kent, Applied Physics Letters **109**, 082401 (2016).
[5] H. Gan, R. Malmhall, Z. Wang, B. K. Yen, J. Zhang, X. Wang, Y. Zhou, X. Hao, D. Jung, K. Satoh *et al.*, Applied Physics Letters **105**, 192403 (2014).
[6] J. F. Sierra, F. G. Aliev, R. Heindl, S. E. Russek, and W. H. Rippard, Applied Physics Letters **94**, 012506 (2009).
[7] J. M. Shaw, H. T. Nembach, T. J. Silva, and C. T. Boone, Journal of Applied Physics **114**, 243906 (2013).
[8] B. Heinrich, J. F. Cochran, and R. Hasegawa, Journal of Applied Physics **57**, 3690 (1985).
[9] M. Konoto, H. Imamura, T. Taniguchi, K. Yakushiji, H. Kubota, A. Fukushima, K. Ando, and S. Yuasa, Applied Physics Express **6**, 073002 (2013).
[10] J. J. Kan, M. Gottwald, C. Park, X. Zhu, and S. H. Kang, IEEE Transactions on Magnetics **51**, 1 (2015).
[11] D. B. Gopman, D. Bedau, S. Mangin, C. H. Lambert, E. E. Fullerton, J. A. Katine, and A. D. Kent, Applied Physics Letters **100**, 062404 (2012).
[12] D. B. Gopman, D. Bedau, S. Mangin, E. E. Fullerton, J. A. Katine, and A. D. Kent, Journal of Applied Physics **115**, 17C707 (2014).
[13] R. D. McMichael, Journal of Applied Physics **103**, 07B114 (2008).