

Double CoFeB Reference Layers for Optimized PMA and BEOL Compatibility of SOT-MRAM

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Supplementary Information

Table of Content

Supplementary Information S1: Quantitative evaluation of effective magnetic anisotropy energy density (K_{eff}).

Supplementary Information S2: Detailed Current-in-Plane Tunneling (CIPT) Measurements and Analysis.

Supplementary Information S3: Optimization of the SAF Pinning Layers.

Supplementary Information S1. Quantitative evaluation of effective magnetic anisotropy energy density (K_{eff})

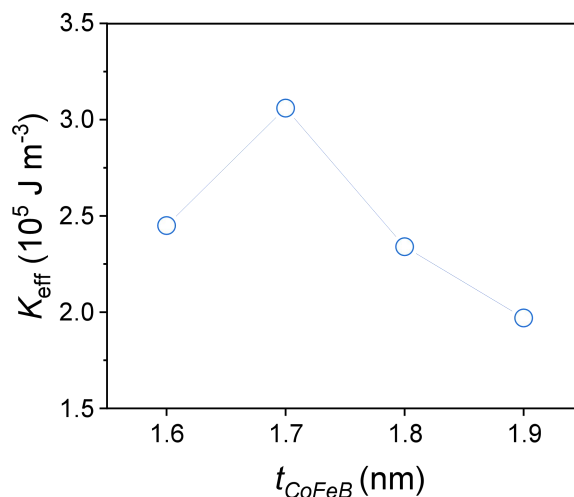
To provide a rigorous quantitative evaluation of the perpendicular magnetic anisotropy (PMA) enhancement in the double CoFeB (DCFB) reference layer structure, we calculated the effective magnetic anisotropy energy density (K_{eff}). The calculations were based on the experimental saturation magnetization (M_s) and the anisotropy field (H_K extracted from Vibrating Sample Magnetometer (VSM) measurements. The K_{eff} values were determined by:

$$K_{\text{eff}} = \frac{M_s H_K}{2},$$

the quantitative results were extracted for the W/CoFeB(1.1 nm)/MgO/CoFeB(t)/W/Ta partial stacks, where the total CoFeB thickness (t_{CoFeB}) was varied from 1.6 nm to 1.9 nm (corresponding to an upper CoFeB thickness ranging from 0.5 nm to 0.8 nm). The detailed magnetic parameters for each thickness are summarized in Table S1.

Table1 Magnetic parameters of DCFB films with various thicknesses.

t_{CoFeB} (nm)	M_s (10^5 A/m)	$\mu_0 H_K$ (T)	K_{eff} (10^5 J/m ³)
1.6	6.44	0.76	2.45
1.7	7.11	0.86	3.06
1.8	6.41	0.73	2.34
1.9	5.79	0.68	1.97



Supplementary Fig. S1 Dependence of effective magnetic anisotropy energy density (K_{eff}) on total CoFeB thickness (t_{CoFeB}) for the CoFeB(1.1 nm)/W/CoFeB(t_{CoFeB})/ stacks.

As illustrated in Table S1 and Fig. S1, the K_{eff} exhibits a distinct and highly optimized trend. Specifically, when the total CoFeB thickness reaches 1.7 nm (i.e., an upper CoFeB layer thickness of 0.6 nm), the K_{eff} achieves a remarkable maximum value of approximately $3.06 \times 10^5 \text{ J/m}^3$.

This robust quantitative value serves as strong, direct evidence for the PMA enhancement claimed in our study. For comparison, in conventional single CoFeB layers employing W buffer and capping layers, the K_{eff} is typically limited to a range of approximately $1 \sim 2 \times 10^5 \text{ J/m}^3$ [1]. Furthermore, for single CoFeB structures, the critical thickness for maintaining PMA is strictly restricted. The substantial enhancement observed here firmly confirms that utilizing the heavy-metal bridged DCFB structure effectively multiplies the interfacial anisotropy contributions, allowing the stack to sustain a massive positive K_{eff} even at a large total CoFeB thickness of 1.7 nm.

References

- [1]. An G G, Lee J B, Yang S M, et al. Highly stable perpendicular magnetic anisotropies of CoFeB/MgO frames employing W buffer and capping layers[J]. Acta Materialia, 2015, 87: 259-265.

Supplementary Information S2. Detailed Current-in-Plane Tunneling (CIPT) Measurements and Analysis

To properly assess the reliability of the extracted TMR ratios and resistance-area (RA) products, we performed comprehensive CIPT measurements. The data acquisition and extraction analysis strictly followed the standard methodology described in the References [1].

Below, we explicitly demonstrate the detailed CIPT measurement and extraction process using the DCFB stack (exhibiting a TMR of $\sim 118\%$) as a representative example. Furthermore, the comprehensive raw CIPT datasets for all investigated DCFB stacks are provided at the end of this section to ensure complete data transparency.

1. Representative CIPT Analysis (Optimal DCFB Sample)

1.1. Probe Spacing and Raw Resistance Measurements

The CIPT measurements were performed over a range of mean probe distances from $3\text{ }\mu\text{m}$ to $59\text{ }\mu\text{m}$. The raw parameters and probe-distance-dependent resistance measurements were systematically recorded under opposite magnetic field conditions (parallel and antiparallel states), as presented in Fig. S2-1 and Fig. S2-2.

Rt [$\Omega/\square$]	29.959
Rb [$\Omega/\square$]	3.988
RA1 [$\Omega\text{ }\mu\text{m}^2$]	7843.961
RA2 [$\Omega\text{ }\mu\text{m}^2$]	1.717E+4
TMR [%]	118.916
λ [μm]	15.20
R²	1.000

Fig. S2-1. Raw data of parameters from probe-distance-dependent CIPT measurements for the DCFB-based MTJ stack.

H1 measurement set

Mean x [μm]	$R_{\square}$ [$\Omega/\square$]	$R_{\square}$ [$\Omega/\square$] pos. corrected	Field [T/ μ_0]
59.00	4.040	4.058	-7863.451
39.00	5.610	5.610	-7817.621
26.00	9.006	8.902	-8224.358
22.00	10.717	10.740	-8035.311
13.00	17.217	16.999	-7932.195
9.00	21.414	21.414	-8081.141
6.00	24.576	24.536	-7874.908
3.00	27.713	27.975	-7937.924
3.00	29.477	27.684	-8069.683

H2 measurement set

Mean x [μm]	$R_{\square}$ [$\Omega/\square$]	$R_{\square}$ [$\Omega/\square$] pos. corrected	Field [T/ μ_0]
3.00	30.625	28.867	1.844E+4
3.00	28.439	28.706	1.860E+4
6.00	26.661	26.774	1.863E+4
9.00	24.800	24.800	1.853E+4
13.00	21.394	21.245	1.834E+4
22.00	15.510	15.531	1.828E+4
26.00	13.507	13.409	1.852E+4
39.00	8.731	8.731	1.851E+4
59.00	5.433	5.473	1.825E+4

Fig. S2-2. Raw data of probe-distance-dependent resistance measurements under opposite (parallel and antiparallel) magnetic field conditions.

1.2. Sheet Resistance ($R_{\square}$) Extraction

Based on the raw resistance data, the position-corrected sheet resistance ($R_{\square}$) values for both the parallel (P) and antiparallel (AP) magnetic states were extracted and plotted as a function of the probe spacing (Fig. S2-3).

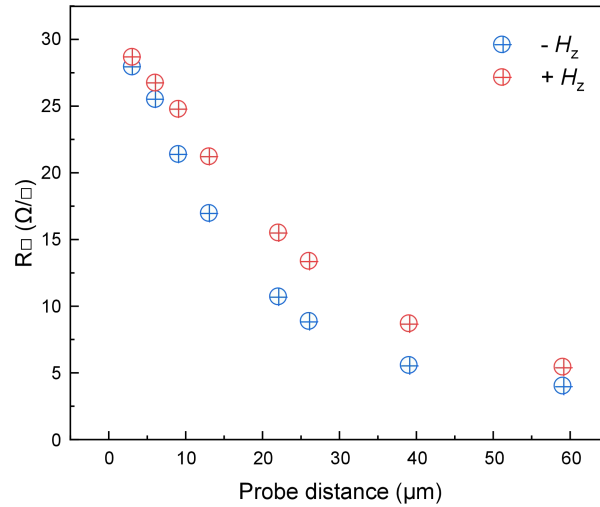


Fig. S2-3. Position-corrected sheet resistance ($R_{\square}$) of the MTJ films as a function of probe distance under opposite magnetic field directions.

2. Comprehensive CIPT Datasets for DCFB Stacks

To ensure complete experimental transparency, the CIPT result data for DCFB-based stacks with varying lower CoFeB thicknesses from 0.9-1.2 nm are compiled below.

Rt [$\Omega/\square$]	30.044
Rb [$\Omega/\square$]	4.094
RA1 [$\Omega \mu\text{m}^2$]	6561.566
RA2 [$\Omega \mu\text{m}^2$]	1.177E+4
TMR [%]	79.360
λ [μm]	13.86
R ²	1.000

Fig. S2-4. CIPT test result for DCFB CoFeB(0.9)/W/CoFeB(0.6).

Rt [$\Omega/\square$]	29.706
Rb [$\Omega/\square$]	4.016
RA1 [$\Omega \mu\text{m}^2$]	8453.103
RA2 [$\Omega \mu\text{m}^2$]	1.662E+4
TMR [%]	96.591
λ [μm]	15.83
R ²	1.000

Fig. S2-5. CIPT test result for DCFB CoFeB(1.0)/W/CoFeB(0.6).

Rt [$\Omega/\square$]	29.842
Rb [$\Omega/\square$]	3.979
RA1 [$\Omega \mu\text{m}^2$]	8990.540
RA2 [$\Omega \mu\text{m}^2$]	1.882E+4
TMR [%]	109.282
λ [μm]	16.30
R ²	1.000

Fig. S2-6. CIPT test result for DCFB CoFeB(1.1)/W/CoFeB(0.6).

Rt [$\Omega/\square$]	29.959
Rb [$\Omega/\square$]	3.988
RA1 [$\Omega \mu\text{m}^2$]	7843.961
RA2 [$\Omega \mu\text{m}^2$]	1.717E+4
TMR [%]	118.916
λ [μm]	15.20
R ²	1.000

Fig. S2-7. CIPT test result for DCFB CoFeB(1.2)/W/CoFeB(0.6).

As shown in the CIPT test results, the slight RA variations attributed to the thickness non-uniformity of the sputtered MgO barrier on the wafer.

References

- [1]. Worledge D C, Trouilloud P L. Magnetoresistance measurement of unpatterned magnetic tunnel junction wafers by current-in-plane tunneling[J]. Applied Physics Letters, 2003, 83(1): 84-86.

Supplementary Information S3. Optimization of the SAF Pinning Layers

As discussed in the main text, a slight TMR decrease was observed at large negative magnetic fields in the initial DCFB-based MTJ after 400°C annealing (main text Fig. 5(b)). This behavior indicates a partial canting and slight instability of the reference layer. The underlying mechanism for this behavior is attributed to the initial, unoptimized growth conditions, under which the upper [Co/Pt] SAF pinning layers exhibited a suboptimal crystallization state following the 400°C annealing process. This degraded crystallization slightly weakened the RKKY exchange coupling, causing the reference layer to yield partially under high external magnetic fields.

To demonstrate that this high-field instability can be completely resolved, we conducted further structural and process optimizations on the SAF layers. By refining the sputtering process conditions and precisely tuning the individual thicknesses of the Pt and Co layers, the crystallization quality of the SAF was significantly improved.

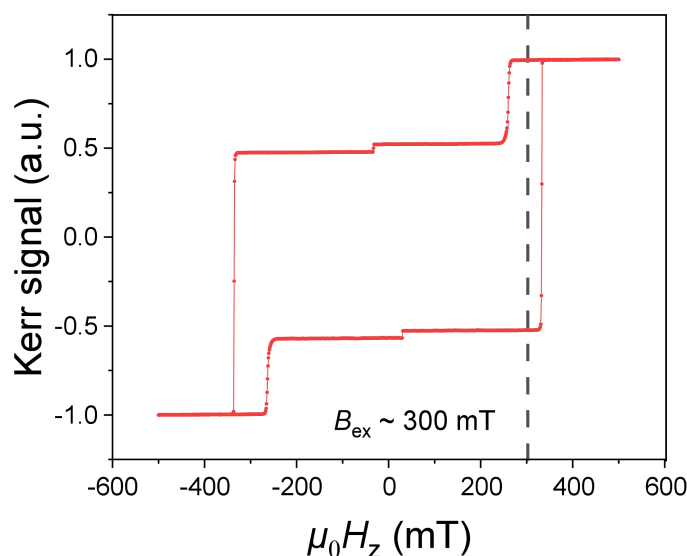


Fig. S3-1. Polar magneto-optical Kerr effect (PMOKE) hysteresis loop of the fully optimized DCFB-based MTJ stack.

As shown in Fig. S3-1, the fully optimized structure yields a highly robust reference layer characterized by perfectly square hysteresis loops after annealed 400°C. The improved crystallization of the optimized SAF provides a massive RKKY exchange field (B_{ex}) of approximately 300 mT, eliminating the high-field canting effect. These results confirm that while an unoptimized SAF can lead to minor reference layer yielding, the proposed DCFB reference layer design itself is highly stable and capable

of maintaining robust PMA and rigid pinning when paired with properly optimized pinning layers.