# Supporting information

# Exchange bias induced by the spin glass-like phase in multifunctional ferrimagnetic $CoFe_2O_4$ thin films†

Songjiang He,‡[a] Shuang Pan, ‡[a] Lang Cheng,[a] Sichao Dai,[a] Xiuhao Mo,[b] Chao Wang,[b] Fangchao Long,[c] Shengqiang Zhou[c] and Yu-Jia Zeng*[a]

[a] Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, P. R. China

[b] Institute of Nanosurface Science and Engineering, Guangdong Provincial Key Laboratory of Micro/Nano Optomechatronics Engineering, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen 518060, China

[c] Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Dresden 01328, Germany

† Electronic supplementary information (ESI) available.

‡ Equally contributed to this work.

* Corresponding authors (E-mail: yjzeng@szu.edu.cn (Zeng YJ))

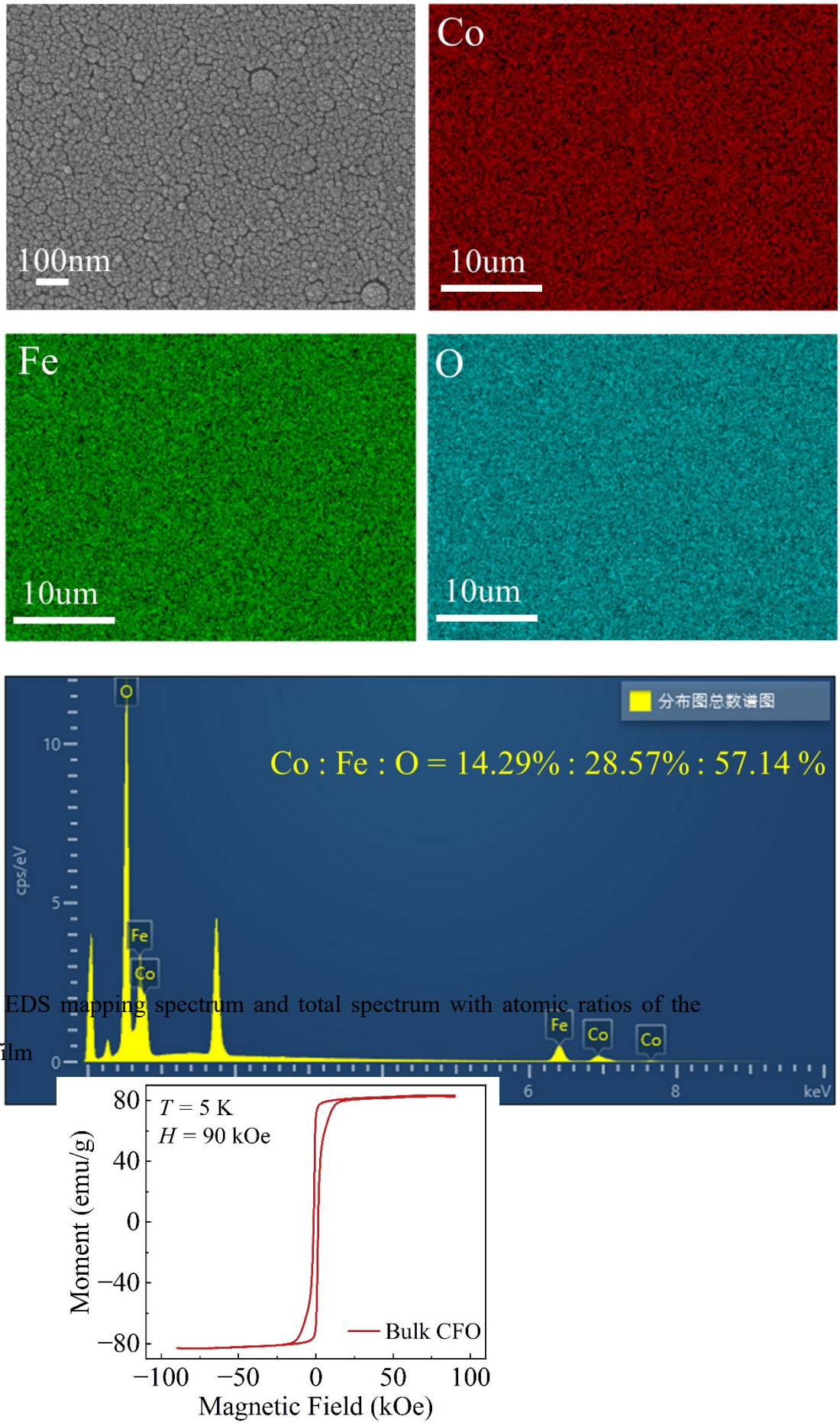


**Fig. S1** SEM, EDS mapping spectrum and total spectrum with atomic ratios of the $CoFe_2O_4$ thin film




**Fig. S2** Magnetic hysteresis of the bulk CFO at 5 K.

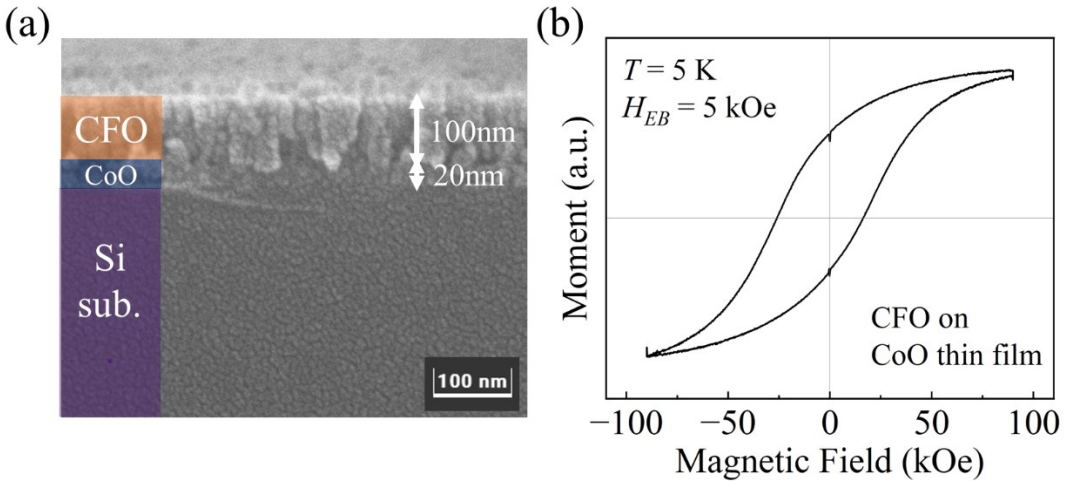


**Fig. S3** (a) Cross-sectional SEM image of the CFO/CoO bilayer thin films. (b) Magnetic hysteresis of the CFO/CoO heterostructure. The $H_{EB}$ is approximately 5 kOe.

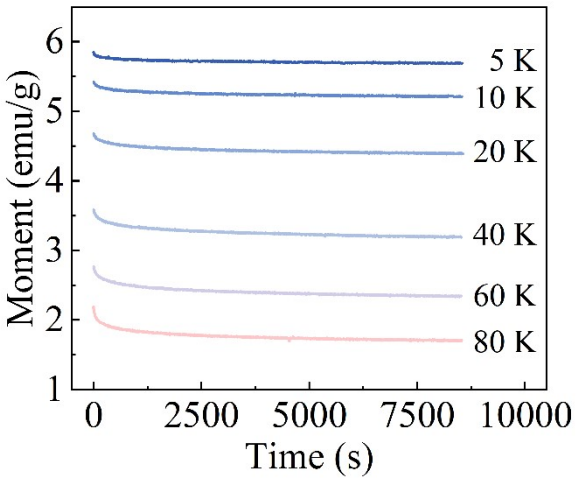


**Fig. S4** Isothermal magnetization relaxation at different temperatures after field cooling 90 kOe.

**Table S1** Exchange bias of different materials.

| Types | Materials | Phase | $T$ (K) | $H_C$ (kOe) | $H_{EB}$ (kOe) | Reference |
|---|---|---|---|---|---|---|
| Thin films | CFO | FIM/SG | 5 | 25.1 | 11.1 | This work |
| Thin films | CFO | FM/AFM | 20 | 11.8 | 0.9 | [1] |
| Thin films | NCO | FM/AFM | 10 | 1.4 | 1.6 | [2] |
| Thin films | LMO | FM/AFM | 5 | 1.263 | 0.302 | [3] |
| Thin films | NMS | FM/AFM | 10 | 0.226 | 0.221 | [4] |
| Thin films | CrO/TiO | FM/AFM | 10 | 0.27 | 0.15 | [5] |
| Thin films | CuO/Co | FM/AFM | 5 | 2.4 | 0.9 | [6] |
| Thin films | Co/CoO | FM/AFM | 2 | 7.3 | 6.172 | [7] |
| Thin films | CFO/CoO | FM/AFM | 100 | 4.6 | 3.9 | [8] |
| Thin films | Co/ZnO | FM/AFM | 10 | 1.6 | 0.963 | [9] |
| Thin films | EuSi2 | FM/AFM | 2 | 1.1 | 0.5 | [10] |
| Thin films | NNMO | FM/SG | 2 | 1.5 | 0.532 | [11] |
| Thin films | MNCT | FM/SG | 2 | 0.47 | 0.098 | [12] |
| Thin films | CuMn | FM/SG | 5 | 1.5 | 1.4 | [13] |
| Thin films | FeAu/FeNi | FM/SG | 2 | 0.270 | 0.110 | [14] |
| Thin films | MFO/Si | FM/SG | 10 | 0.54 | 0.19 | [15] |
| Bulk | MNS | FIM/SG | 2 | 2.19 | 10.19 | [16] |
| Bulk | HFM | FIM/SG | 5 | 20.5 | 4.6 | [17] |
| Bulk | NMG | FM/AFM | 2 | 4 | 6 | [18] |
| Bulk | GCMO | FM/AFM | 5 | 0.5 | 0.311 | [19] |
| Bulk | NMAS | FM/AFM | 2 | 3.8 | 2.5 | [20] |
| Bulk | LSMO | FM/SG | 2 | 4 | 2.52 | [21] |
| Bulk | MNS | AFM/SG | 2 | 0.515 | 3.52 | [22] |
| Bulk | LFSO | AFM/SG | 2 | 1.2 | 0.450 | [23] |
| Bulk | NMIF | AFM/SG | 5 | 2 | 5.3 | [24] |
| Bulk | NCMS | AFM/SG | 3 | 1.7 | 7 | [25] |

| | | | | | | |
|---|---|---|---|---|---|---|
| Bulk | NMI | AFM/SG | 10 | 1.7 | 1.35 | [26] |
| 2D | MCS | AFM/SG | 2 | 0.395 | 1.625 | [27] |
| Powder | MCN | FIM/SG | 5 | 10 | 12 | [28] |
| Powder | LSCFO | FM/AFM | 5 | 12.8 | 1.2 | [29] |
| Powder | LCCFO | FIM/SG | 5 | 2 | 15.6 | [30] |
| Powder | CFO | FM/AFM | 10 | 12.6 | 0.569 | [31] |

## Reference


1 D. Yang, Y. Yun, A. Subedi, N. E. Rogers, D. M. Cornelison, P. A. Dowben and X. Xu, *Phys. Rev. B*, 2021, **103**, 224405.

2 D. Yang, A. Subedi, C. Liu, H. Ambaye, V. Lauter, P. A. Dowben, Y. Liu and X. Xu, *Adv. Electron. Mater.*, 2025, **11**, 2400149.

3 G. Zhou, H. Ji, Y. Bai, Z. Quan and X. Xu, *Sci. China Mater.*, 2019, **62**, 1046–1052.

4 Y. Ling, Y. Hu, H. Wang, B. Niu, J. Chen, R. Liu, Y. Yuan, G. Wang, D. Wu, M. Xu, Z. Han, J. Du and Q. Xu, *ACS Appl. Mater. Interfaces*, 2021, **13**, 24285–24294.

5 W. Yuan, T. Su, Q. Song, W. Xing, Y. Chen, T. Wang, Z. Zhang, X. Ma, P. Gao, J. Shi and W. Han, *Sci. Rep.*, 2016, **6**, 28397.

6 M. Gamino, A. M. H. De Andrade, J. L. Salazar Cuaila, J. E. Schmidt, V. Skumryev and J. Geshev, *J. Magn. Magn. Mater.*, 2018, **449**, 5–9.

7 Y. Sun, W. Tang, S. Chen, L. Liu, H. Liu, J. Ge, X. Zhang, W. Jiang, H. Liang and Y. Zeng, *Adv. Phys. Res.*, 2023, **2**, 2200066.

8 T. D. Ha, J.-W. Chen, M. Yen, Y.-H. Lai, B.-Y. Wang, Y.-Y. Chin, W.-B. Wu, H.-J. Lin, J.-Y. Juang and Y.-H. Chu, *ACS Appl. Mater. Interfaces*, 2020, **12**, 46874–46882.

9 X. Liao, C. Wang, D. Zhao, W. Tang, H. Liang, Y.-J. Zeng, C. Van Haesendonck, Q. Song and H. Liu, *Appl. Phys. Rev.*, 2024, **11**, 041405.

10 D. V. Averyanov, I. S. Sokolov, A. N. Taldenkov, O. E. Parfenov, I. A. Karateev, O. A. Kondratev, A. M. Tokmachev and V. G. Storchak, *Nanoscale Horiz.*, 2023, **8**, 803–811.

11 A. K. Singh, S. Chauhan and R. Chandra, *Appl. Phys. Lett.*, 2017, **110**, 102402.

12 Y. Ling, Y. Hu, X. Chi, J. Chen, H. Wang, B. Niu, D. Wu, M. Xu, Z. Han, J. Du and Q. Xu, *J. Appl. Phys.*, 2022, **131**, 173902.

13 P. Liu, B. Lv, Y. Wang, P. Chen, L. Wang and C. Gao, *Phys. Rev. B*, 2024, **109**, 184412.

14 X. Chi, W. Rui, J. Du, S. Zhou, A. Du and Y. Hu, *Appl. Phys. Lett.*, 2016, **108**, 172401.

15 K. Mallick and P. S. Anil Kumar, *J. Appl. Phys.*, 2018, **124**, 053901.

16 J. Sharma, S. Gopinatha Warrier, M. M. Raja and A. Alam, *ACS Appl. Electron. Mater.*, 2024, **6**, 6356–6364.

17 H. Zhou, Y. Cao, S. Khmelevskyi, Q. Zhang, S. Hu, M. Avdeev, C.-W. Wang, R. Zhou, C. Yu, X. Chen, Q. Li, J. Miao, Q. Li, K. Lin and X. Xing, *J. Am. Chem. Soc.*, 2024, **146**, 20770–20777.
18 F. Tian, X. Ke, K. Cao, D. Wang, Q. Zhao, J. Li, Z. Dai, D. Wang, Y. Zhang, C. Zhou, Y. Wang, W. Zuo, M. Fang and S. Yang, *APL Mater.*, 2021, **9**, 011104.
19 C. Li, W. Yang, Y. Lu, Y. Yang, C. Wang, Q. Lei, Y. Qiu and Y. Luo, *Appl. Phys. Lett.*, 2023, **123**, 172406.
20 R. Singh, B. Ingale, L. K. Varga, V. V. Khovaylo and R. Chatterjee, *Phys. B Condens. Matter*, 2014, **448**, 143–146.
21 S. Karmakar, S. Taran, E. Bose, B. K. Chaudhuri, C. P. Sun, C. L. Huang and H. D. Yang, *Phys. Rev. B*, 2008, **77**, 144409.
22 J. Sharma and K. G. Suresh, *Appl. Phys. Lett.*, 2015, **106**, 072405.
23 S. Banerjee, D. P. Panda, P. Yanda and A. Sundaresan, *Phys. Rev. Mater.*, 2023, **7**, 034405.
24 X. Liao, L. Gao, Y. Wang, X. Xu, M. T. Khan, T. Chang, K. Chen, Y.-J. Zeng, S. Yang and P. Svedlindh, *Sci. China Mater.*, 2020, **63**, 1291–1299.
25 X. Liao, S. Wei, Y. Wang, D. Wang, K. Wu, H. Liang, S. Yang, P. Svedlindh and Y. Zeng, *Adv. Phys. Res.*, 2023, **2**, 2200043.
26 B. M. Wang, Y. Liu, P. Ren, B. Xia, K. B. Ruan, J. B. Yi, J. Ding, X. G. Li and L. Wang, *Phys. Rev. Lett.*, 2011, **106**, 077203.
27 R. A. Murphy, L. E. Darago, M. E. Ziebel, E. A. Peterson, E. W. Zaia, M. W. Mara, D. Lussier, E. O. Velasquez, D. K. Shuh, J. J. Urban, J. B. Neaton and J. R. Long, *ACS Cent. Sci.*, 2021, **7**, 1317–1326.
28 L. Ding, L. Chu, P. Manuel, F. Orlandi, M. Li, Y. Guo and Z. Liu, *Mater. Horiz.*, 2019, **6**, 318–325.
29 R. C. Sahoo, Y. Takeuchi, A. Ohtomo and Z. Hossain, *Phys. Rev. B*, 2019, **100**, 214436.
30 P. Singh, R. K. Singh, S. Dixit, N. Patel, M. Alam, S. Dan, A. Jain, K. Anand, V. K. Gangwar, R. Singh, A. G. Joshi, S. M. Yusuf and S. Chatterjee, *J. Phys. Condens. Matter*, 2022, **34**, 375803.
31 B. Rivas-Murias, M. Testa-Anta, A. S. Skorikov, M. Comesaña-Hermo, S. Bals and V. Salgueiriño, *Nano Lett.*, 2023, **23**, 1688–1695.