with predictions from a model for thermally induced magnetization reversal [9].

B. MNP measurements with Nb nanoSQUIDs

Nb nanoSQUIDs have been integrated into the torque magnetometer setup of the Poggio group at Univ. Basel to investigate individual Ni, permalloy and CoFeB nanotubes. The combined system enables simultaneous measurements of the integral magnetization by dynamic cantilever torque magnetometry and local magnetization by nanoSQUID magnetometry [13]. Combined torque and SQUID measurements on individual Ni nanotubes, supported by micromagnetic simulations of magnetization configurations, suggest reversal via the formation of vortexlike states within the nanotube [22]. Such stray-field free states can have applications for memory and noninvasive sensing.

CONCLUSIONS AND OUTLOOK

YBCO and Nb nanoSQUIDs have been developed for the investigation of magnetization reversal of individual magnetic nanoparticles. Very small SQUID inductances enable the realization of ultralow flux noise of the nanoSQUIDs in the thermal white noise limit. For MNPs placed in 10 nm distance to the SQUID loop, this translates into spin sensitivities down to only a few Bohr magnetons per unit bandwidth, which is appropriate for many studies on individual MNPs. Apart from further suppression of $1/f$ noise, a key challenge is the development of reliable routines for placing MNPs in a controlled way in close vicinity to the nanoSQUIDs, ideally at variable position and temperature. For YBCO nanoSQUIDs, the recently developed creation of Josephson junctions and SQUIDs by focused He ion irradiation [23, 24] can provide new perspectives for creating advanced nanoscale devices

REFERENCES

[1] W. Wernsdorfer, K. Hasselbach, D. Mailly, B. Barbara, A. Benoit, L. Thomas, and G. Suran, "DC-SQUID magnetization measurements of single magnetic particles," J. Magn. Magn. Mater., vol. 145, pp. 33-39, 1995.

[2] W. Wernsdorfer, "Classical and quantum magnetization reversal studied in nanometersized particles and clusters," Adv. Chem. Phys., vol. 118, pp. 99-190, 2001.

[3] C. Granata, and A. Vettoliere, "Nano superconducting quantum interference device: A powerful tool for nanoscale investigations," Phys. Rep., vol. 614, pp. 1-69, 2016.

[4] M. J. Martínez-Pérez, and D. Koelle, "NanoSQUIDs: Basics & recent advances," Phys. Sci. Rev., vol. 2, 20175001, 2017.

[5] H. Hilgenkamp, and J. Mannhart, "Grain boundaries in high-T_c superconductors," Rev. Mod. Phys., vol. 74, pp. 485-549, 2002.

[6] J. Nagel, K. B. Konovalenko, M. Kemmler, M. Turad, R. Werner, E. Kleisz, S. Menzel, R. Klingeler, B. Büchner, R. Kleiner, and D. Koelle, "Resistively shunted $YBa_2Cu_3O_7$ grain boundary junctions and low-noise SQUIDs patterned by a focused ion beam down to 80 nm linewidth," Supercond. Sci. Technol., vol. 24, 015015, 2011.

[7] T. Schwarz, J. Nagel, R. Wölbing, M. Kemmler, R. Kleiner, and D. Koelle, "Low-noise superconducting quantum interference device operating in tesla magnetic fields," ACS Nano, vol. 7, pp. 844-850, 2013.

[8] T. Schwarz, R. Wölbing, C. F. Reiche, B. Müller, M. J. Martínez-Pérez, T. Mühl, B. Büchner, R. Kleiner and D. Koelle, "Low-noise $YBa_2Cu_3O_7$ nano-SQUIDs for performing magnetization reversal measurements on magnetic nanoparticles," Phys. Rev. Applied, vol. 3, 044001, 2015.

[9] M. J. Martínez-Pérez, B. Müller, D. Korinski, R. Kleiner, J. Sesé, and D. Koelle, "NanoSQUID magnetometry of individual cobalt nanoparticles grown by focused electron beam induced deposition," Supercond. Sci. Technol., vol. 30, 024003, 2017.

[10] D. Hagedorn, O. Kieler, R. Dolata, R. Behr, F. Müller, J. Kohlmann, and J. Niemeyer, "Modified fabrication of planar sub-µm superconductor–normal metal–superconductor Josephson junctions for use in a Josephson arbitrary waveform synthesizer," Supercond. Sci. Technol., vol. 19, pp. 294-298, 2006.

[11] J. Nagel, O. F. Kieler, T. Weimann, R. Wölbing, J. Kohlmann, A. B. Zorin, R. Kleiner, D. Koelle, and M. Kemmler, "Superconducting quantum interference devices with submicron Nb/HfTi/Nb junctions for investigation of small magnetic particles," Appl. Phys. Lett., vol. 99, 032506, 2011.

[12] R. Wölbing, J. Nagel, T. Schwarz, O. Kieler, T. Weimann, J. Kohlmann, A. B. Zorin, M. Kemmler, R. Kleiner, and D. Koelle, "Nb nano superconducting quantum interference devices with high spin sensitivity for operation in magnetic fields up to 0.5 T," Appl. Phys. Lett., vol. 102, 192601, 2013.

[13] J. Nagel *et al.*, "Nanoscale multifunctional sensor formed by a Ni nanotube and a scanning Nb nanoSQUID," Phys. Rev. B, vol. 88, 064425, 2013.

[14] M. M. Khapaev, M. Yu. Kupriyanov, E. Goldobin, and M Siegel, "Current distribution simulation for superconducting multi-layered structures," Supercond. Sci. Technol., vol. 16, pp. 24-27, 2003.

[15] R. Wölbing, T. Schwarz, B. Müller, J. Nagel, M. Kemmler, R. Kleiner, and D. Koelle, "Optimizing the spin sensitivity of grain boundary junction nanoSQUIDs—towards detection of small spin systems with single-spin resolution," Supercond. Sci. Technol., vol. 27, 125007, 2014.

[16] D. Koelle, R. Kleiner, F. Ludwig, E. Dantsker, and J. Clarke, "High-transition-temperature superconducting quantum interference devices," Rev. Mod. Phys., vol. 71, pp. 631-686, 1999.

[17] A. H. Miklich, D. Koelle, T. J. Shaw, F. Ludwig, D. T. Nemeth, E. Dantsker, J. Clarke, N. McN Alford, and T. W. Button, "Low-frequency excess noise in $YBa_2Cu_30_{7-x}$ dc superconducting quantum interference devices cooled in static magnetic fields," Appl. Phys. Lett., vol. 64, pp. 3494-3496, 1994.

[18] V. Morosh *et al.*, "Transport and noise properties of sub-100 nm planar Josephson junctions with metallic barrier for nanoSQUID applications," unpublished.

[19] M. J. Martínez-Pérez, D. Gella, B. Müller, V. Morosh, R. Wölbing, J. Sesé, O. Kieler, R. Kleiner, and D. Koelle, "Three-axis vector vector nano superconducting quantum interference device," ACS Nano, vol. 10, pp. 8308-8315, 2016.

[20] M. J. Martínez-Pérez, J. Pablo-Navarro, B. Müller, R. Kleiner, C. Magén, D. Koelle, J. M. de Teresa, and J. Sesé, "NanoSQUID magnetometry on individual as-grown and annealed Co nanowires at variable temperature," Nano Lett., vol. 18, 7674-7682, 2018.

[21] J. Pablo-Navarro, C. Magén, and J. M. de Teresa, "Purified and crystalline three-dimensional electron-beam-induced deposits: The successful case of cobalt for high performance magnetic nanowires," ACS Appl. Nano Mater., vol. 1, pp. 38-46, 2018.

[22] A. Buchter *et al.*, "Reversal mechanism of an individual Ni nanotube simultaneously studied by torque and SQUID magnetometry," Phys. Rev. Lett., vol. 111, 067202, 2013.

[23] S. A. Cybart, E. Y. Cho, J. T. Wong, B. H. Wehlin, M. K. Ma, C. Huynh, and R. C. Dynes, "Nano Josephson superconducting tunnel junctions in $YBa_2Cu_3O_{7-\delta}$ directly patterned with a focused helium ion beam," Nature Nanotechnol., vol. 10, pp. 598-602, 2015.

[24] B. Müller, M. Karrer, F. Limberger, M. Becker, B. Schröppel, C. J. Burkhadt, R. Kleiner, E. Goldobin, and D. Koelle, "Josephson junctions and SQUIDs created by focused helium-ion-beam irradiation of $YBa_2Cu_3O_7$," Phys. Rev. Applied, vol. 11, 044082, 2019.