2021 IEEE 11th International Conference on
"Nanomaterials: Applications & Properties" (NAP-2021)
Odesa, Ukraine, Sept. 5-11, 2021

Superconductivity and Magnetism in 3D Nano-architectures

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Traditionally, the primary field, where curvature is playing a pivotal role, is the theory of general relativity. In recent years, however, the impact of curvilinear geometry enters various disciplines, ranging from solid-state physics over soft-matter physics to chemistry and biology, giving rise to a plethora of emerging domains [1], such as curvilinear nematics, cell biology, semiconductors, superfluidity, optics, plasmonics and 2D van der Waals materials. Furthermore, extending nanostructures into the third dimension has become a major research avenue in modern magnetism [2], superconductivity and spintronics, because of geometry-, curvature- and topology-induced phenomena. This approach provides a means to improve conventional and to launch novel functionalities by tailoring the curvature and 3D shape.

In magnetic materials, the geometrically-broken symmetry provides a new toolbox to change magnetic responses relying on effects extrinsic to the material: curvature-induced anisotropy and chiral responses. These effects are generic and independent of the choice of the magnetic material: any intrinsically achiral isotropic curved ferromagnet acquires chiral and anisotropic responses through the geometrical curvature [2]. In 3D nanomagnetism, of especial interest are artificial 3D frustrated systems, topology- and curvature-induced effects in complex-shaped 3D nano-architectures, and the dynamics of spin waves in 3D magnonic networks.

In superconductors, curvilinear geometry gives rise to topologically nontrivial screening currents and confinement potentials that stipulate the occurrence of different patterns of topological defects of the superconducting order parameter (Abrikosov vortices) and slips of its phase [1]. The extension of superconducting nanostructures into the third dimension has already been demonstrated to improve the performance of superconducting quantum interference devices (SQUIDs), microwave bolometers and it advances investigations of 3D fluxonic circuits with complex interconnectivity.

However, traditional thin-film techniques insufficiently suit the demands of 3D magnetism and superconductivity. This stipulates the increasingly growing attention to strain-driven self-rolling and additive manufacturing nanotechnologies. In recent years, 3D direct writing by focused electron and ion beam-induced deposition (FEBID and FIBID) has become the technique of choice for the fabrication of complex-shaped 3D nano-architectures [3]. Given their lateral resolution down to 10 nm and versatility regarding the substrate material, FEBID and FIBID appear as promising nanofabrication technologies for 3D magnetism, superconductivity and magnon spintronics.

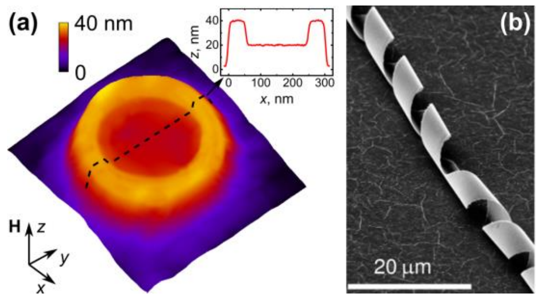

Fig. 1. (a) AFM image of a ferromagnetic Co-Fe nanovolcano fabricated by FEBID [4]. Inset: cross-sectional line scan, as indicated. (b) SEM image of a superconducting Nb nanohelix bolometer fabricated by the strain-driven self-rolling technology [5].

The state of the art, current challenges and perspectives of 3D nanofabrication for superconductivity and magnetism will be outlined in the presentation. Two examples of ferromagnetic and superconducting 3D nano-architectures are presented in Fig. 1. Due to the strongly non-uniform demagnetizing field [4], by varying the crater diameter of the nanovolcano, the high-frequency spin-wave eigenmodes can be tuned without affecting the lowest-frequency mode. Thereby, the extension of 2D nanodisks into the third dimension allows one to engineer their lowest eigenfrequency by using 3D nanovolcanoes with 30% smaller footprints. Due to the significantly smaller film area in contact with the substrate (negligible heat sink), the noise-equivalent-power for the Nb nanohelix microwave bolometer is about four orders of magnitude smaller than that for a commercially available sensor made of a 2D superconducting film [5]. In addition, the screening currents in the nanohelix are topologically nontrivial (multiply connected) that leads to a peculiar interplay of Abrikosov-vortex clusters with phase-slip lines.

References

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