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Bloch-point-mediated topological transformations of magnetic domain walls in cylindrical nanowires

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Cylindrical nanowires made of soft magnetic materials, in contrast to thin strips, may host domain walls of two distinct topologies. Unexpectedly, we evidence experimentally the dynamic transformation of topology upon wall motion above a field threshold. Micromagnetic simulations highlight the underlying precessional dynamics for one way of the transformation, involving the nucleation of a Bloch-point singularity, however, fail to reproduce the reverse process. This rare discrepancy between micromagnetic simulations and experiments raises fascinating questions in material and computer science.

Directional orders, such as nematics and ferromagnets, may give rise to topologically non-trivial textures of the order parameter. In ferromagnets, the variety of exchange interactions and host systems translates into a broad spectrum of such textures, such as non-zero Chern numbers in band structures on a kagome lattice[1], merons in coupled disks[2] or multilayers[3], chiral domain walls (DWs)[4–6] and skyrmions[7–9]. Yet, while all those have a continuous spin texture, a singular configuration was theoretically predicted in 1965[10]: the Bloch point (BP). This is a point defect for the unit magnetization vector field \mathbf{m} , and as such the only possible topological defect in ferromagnetism[11]. It is the analogue of defects seen in nematic liquid crystals[12, 13], for which the distribution of the director around the defect covers the unit sphere S^2 exactly once. For this reason, an integer called winding number[14] is associated to the BP, which is its signature as a topological defect.

The existence of the BP is crucial, as simulation suggested that the transformation from one spin texture to another of different topology is mediated by a BP expulsion or injection: in static[15] or dynamic[16] magnetization switching of vortex cores in thin films, the nucleation of skyrmions in dots[17] or of DWs in magnetically soft cylindrical nanowires [18]. The latter system appears as a textbook playground for the investigation of topological transformations and of BPs. Indeed, BPs should exist at rest, unlike those involved in the dynamical transformation processes mentioned above. In detail, two types of DWs were predicted to exist in cylindrical nanowires, with different topologies. First is the Bloch point

domain wall (BPW, also called vortex wall by some), hosting a BP at its center even at rest. The BPW was predicted to reach a steady-state motion with high axial velocity even at high magnetic field[19–21]. Second is the transverse-vortex wall (TVW, also called transverse wall by some), with fast azimuthal precession and axial mobility much lower than that of the BPW[19, 22]. Both DWs have been predicted to retain their topology during motion. This makes a sharp contrast with thin strips, prone to DW transformations under both field and spin-polarized current[19, 23, 24]. The latter can be understood as all DWs share a single topology in strips[25], making transformations easier. As the existence of the BPW and TVW has been confirmed experimentally recently at rest[26, 27], the question arises whether the different topology indeed prevents DW transformation in reality.

In this Letter, we investigate the field-driven motion of magnetic DWs in magnetically soft nanowires. Our experiments reveal that the transformation from TVW to BPW and vice-versa may occur. We build a theoretical understanding of this topological transition, associated with the injection of a BP (or expulsion for the reverse process). Micromagnetic simulations partly confirm this qualitative description, highlighting how the precessional magnetization dynamics leads to the previously-overlooked possibility of TVW-to-BPW transformation. However, the BPW-to-TVW transformation is not found in the simulation, leaving open the question whether experiments or models should be blamed.

I. METHODS

Starting from nanoporous alumina templates engineered with two diameter modulations along the pores, we electroplate magnetically-soft $\text{Fe}_{20}\text{Ni}_{80}$ and $\text{Co}_{40}\text{Ni}_{60}$ nanowires [28–30]. The geometry is thus that of a cylinder with a thin section of diameter ≈ 140 nm surrounded by two wider sections of the same diameter ≈ 250 nm, all three with length 10 μm . The purpose of the modulations of diameter is

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