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# Scaling and channelling behavior of helical and skyrmion spin textures in thin films of Te-doped $Cu_2OSeO_3$

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Topologically nontrivial spin textures such as vortices, skyrmions, and monopoles are promising candidates as information carriers for future quantum information science [1]. However, controlled skyrmion manipulation including creation and annihilation remains an important challenge towards not only practical applications but also for the full exploitation of their emergent properties and behaviours. Recently, an intriguing discovery of a new skyrmion phase [2] along with a thermal-fluctuation-induced A-phase skyrmions has been made in multiferroic $Cu_2OSeO_3$ (CSO) crystals, implying richer phase diagrams. The existence of two distinct skyrmion phases in a multiferroic material could be a generic character of underlying physics. Therefore, for deterministic skyrmion-lattice control, magnetic field (H)-temperature (T) phase diagrams are desirable for given materials and boundary conditions.

In this study, we report the systematic control of helical-to-skyrmion phase transitions in thin films of multiferroic Te-doped $Cu_2OSeO_3$ single crystals as function of material thickness, doping, temperature, and magnetic field from direct imaging using *in situ* Lorentz phase microscopy [3]. In thin films with discrete thickness sections, we find that helical-to-skyrmion phase transitions systematically proceed by anisotropic scaling of spiral helical phase periodicities, edge-enhanced skyrmion nucleation, and gradual skyrmion channelling to thicker sections (Figure 1). In our theoretical model, the anisotropic scaling behaviour of helices is attributed to the helix phase tilting towards the field direction, similar to the tilted conical spin spiral observed in bulk measurements with neutron scattering. Based on a series of temperature dependent measurements, the H-T phase diagrams for the both doped and undoped samples are obtained, as shown in Fig. 2. The coloured regions in both cases denote the appearance of the skyrmion phase. Thickness dependences are clearly seen for both samples; the stable H-T space of skyrmion lattices increased with decreasing film thickness.

Our study shows that the skyrmion channelling effectively suppresses the recently reported second skyrmion phase (skyrmion patchness) formation at low temperature and proceeds with edge-selected nucleation. Thickness-dependent gradual skyrmion channelling and enhanced dependence on boundary conditions by Te doping in this study shed new light on the skyrmion lattice manipulation, envisaging the design of skyrmion flow circuits for future spintronics applications.

References

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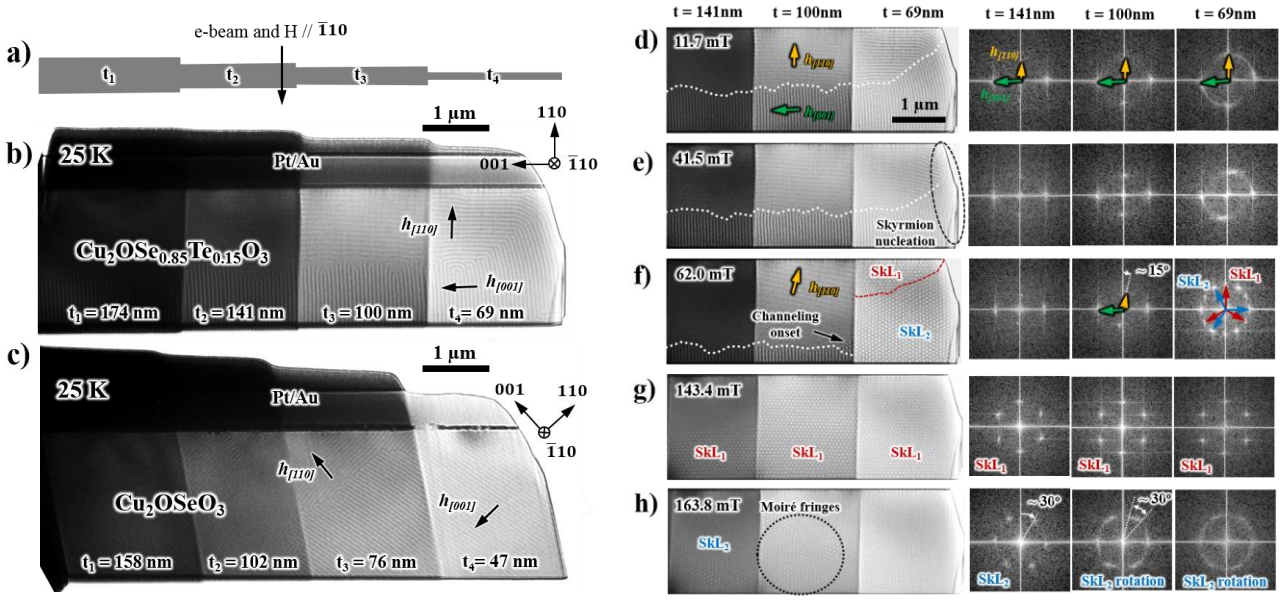


**Figure 1.** Real-space observation of magnetic spin textures in Te-doped and undoped $Cu_2OSeO_3$ thin film. (a-c) Sample schematic and Lorentz images of Te-doped and undoped $Cu_2OSeO_3$. TEM samples at 25 K under the residual magnetic field (H ~ 11mT) along [110] direction. Four different-thickness sections are prepared by focused ion beam for both undoped and doped samples. (d-h) Lorentz images showing helical-to-skyrmion phase transition with increasing magnetic field. FFTs from each thickness sections are shown on the left.

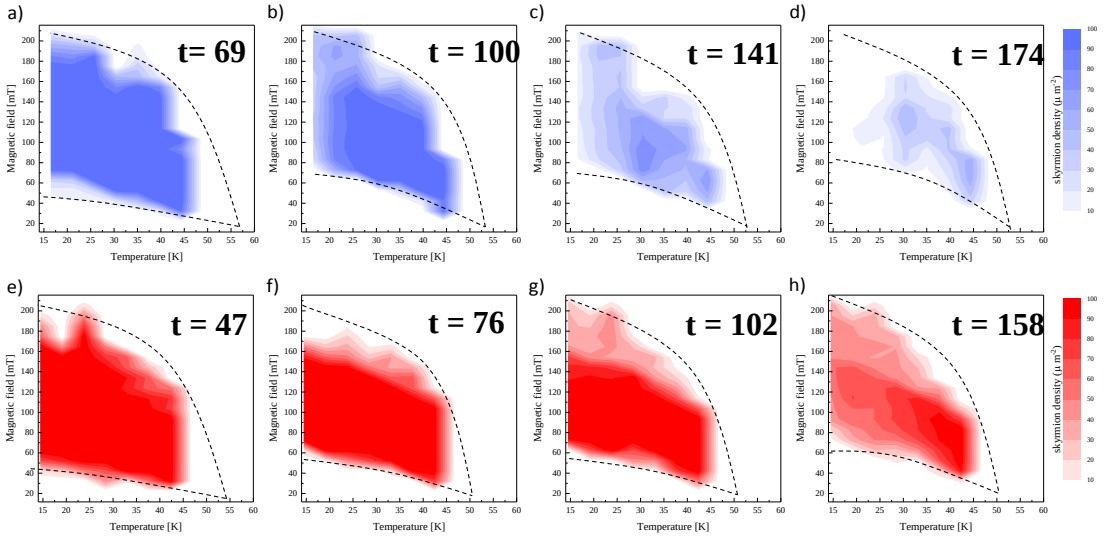


**Figure 2.** Phase diagrams as function of doping and thickness. Magnetic field (H) – temperature (T) phase maps of the both doped (a-d) and undoped (e-h) CSO crystals with increasing film thickness, respectively. The doped sample shows the SkL stability is more strongly dependent on film thickness compared to undoped sample. Both doped and undoped samples show that SkLs are more stable with decreasing film thickness. Times New Roman 12pt. Provide a short description of the figure, including labels and scale markers as appropriate.

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