Exchange coupling, antiphase boundaries, and the origin of self-reversed thermoremanent magnetization

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Self-reversed thermoremanent magnetization (SR-TRM) in the ilmenite-hematite system is thought to result from negative exchange coupling between antiphase domains (APDs) and antiphase domain boundaries (APBs), which form during rapid cooling of the mineral after volcanic eruption. Here we present a study of exchange coupling at APBs using a combination of off-axis electron holography and Monte Carlo simulations. A solid solution containing 70% ilmenite and 30% hematite (ilm70) was synthesised at 1573 K, quenched through the cation ordering phase transition and annealed for 10 hours at 1023 K. The sample was examined using off-axis electron holography, a technique that allows the phase shift of a high-energy electron wave to be recorded in a transmission electron microscope (TEM). Quantitative analysis of the phase shift shows that three distinct types of magnetic wall exist in quenched ilmenite-hematite. The first type corresponds to conventional free-standing 180° Bloch walls. These walls are free to move within the interior of an APD under the influence of an applied magnetic field. The second type forms when a 180° reversal in magnetization coincides exactly with the position of an APB. These walls are referred to as a 180° `chemical' walls. The reversal of magnetization results from negative exchange coupling between adjacent APDs, and occurs without any out-of-plane rotation of the magnetic moments. Chemical walls have a magnetization profile distinct from conventional Bloch walls and have a smaller wall width. A third type of magnetic wall appears when the negative exchange coupling between adjacent APDs is overcome at sufficiently large fields, forcing the magnetization in adjacent APDs to point in the same direction. We refer to these walls as 0° magnetic walls. Monte Carlo simulations have been used to investigate the nature of exchange

coupling between ordered/antiordered APDs and disordered APBs. APBs are enriched in Fe relative to the ordered/antiordered APDs, with enhanced enrichment observed in simulations performed within the hematite-ilmenite miscibility gap. Simulations show no evidence of SR-TRM in systems containing two equally well-ordered ferrimagnetic (FM) domains separated by Fe-enriched AF boundaries. Systems displaying partial long-range order, however, do display SR-TRM. Partial long-range order is characterized by a mixture of highly ordered Ti-rich FM domains and poorly (anti)ordered Fe-rich domains with a weak FM moment. The Fe-enriched antiordered regions fulfill all of the requirements of the x-phase: they are the first to become magnetically ordered on cooling; they are very close to being antiferromagnetic, but carry a small net moment due to partial cation order; they are negatively exchanged-coupled to the neighbouring ordered APDs; they are metastable, appearing only in systems that are partway through the transformation from short- to long-range order. These properties lead to a self-reversal in net magnetisation on cooling.