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Investigation of Spin Manipulation in Pt/$CoFe_2O_4$ via Scanning Transmission Electron Microscopy

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A major goal in quantum science is to create a new generation of devices based on spin manipulation [1]. Through spin manipulation, magnetization can be induced in a nonmagnetic material due to close proximity with a ferromagnetic insulator. This is known as the magnetic proximity effect and has been shown to occur in platinum on cobalt ferrite [1]. $CoFe_2O_4$ is a ferromagnetic insulator with a spinel structure. Spinel oxides have diverse chemical, magnetic, and electric properties, which can be tuned by varying the cation species and coordination environment [2-4].

The spinel structure is a complex structure of the general formula AB_2O_4 with a unit cell of space group Fd-3m. O ions make up an FCC lattice in which 1/8 of the tetrahedral sites and 1/2 of the octahedral sites are occupied. To add to the complexity, the A and B atoms can occupy either the tetrahedral or octahedral sites resulting in two forms of the spinel structure; normal and inverse. In the normal spinel structure, the tetrahedral sites are occupied by divalent ions (A) and the octahedral sites are occupied by trivalent ions (B). Inverse spinels have half of the trivalent atoms occupying the tetrahedral positions and a half occupancy of the trivalent and divalent atoms on octahedral positions. Therefore, the general formula for inverse spinels is $B(AB)O_4$. Few inverse spinel materials meet this criterion, and rather have a fraction of trivalent atoms occupying the tetrahedral sites. This fraction is the degree of inversion and is denoted by λ. A fully inverse spinel would have λ=1 and normal spinel λ=0 [2, 3].

The magnetic properties of cobalt ferrite are directly related to the cation distribution, therefore full characterization of the structure is needed [4]. Here we use high resolution STEM imaging and analytical techniques to investigate the degree of inversion in $CoFe_2O_4$ grown via molecular beam epitaxy. The cross sectional HAADF image in Figure 1(a) shows regions of the expected spinel structure, however a variation in the image contrast is observed across the thin film. We used simulated HAADF images via μSTEM, a S/TEM simulation program based on inelastic scattering, in order to understand the effect of the degree of inversion on the image contrast [5]. The simulated HAADF images of normal spinel (λ=0) and inverse spinel (λ=1) cobalt ferrite (Figure 1(b)) suggest that channeling effects are significant enough to differentiate between normal and inverse spinel. However, the Debye-Waller factor has also been shown to affect the intensity in HAADF imaging [6]. Figure 2 shows HAADF images of the same normal spinel structure simulated using various mean square displacement values found in the literature [1,7]. The simulations show that the mean square displacement affects the intensity of the atomic columns. In this contribution, we will further discuss using simulated and experimental STEM imaging and analytical techniques to investigate the degree of inversion and Debye-Waller factor in cobalt ferrite. We are currently exploring the use of integrated differential phase contrast (iDPC) in combination with electron energy-loss spectroscopy to obtain further experimental data that can be used to refine the simulations.

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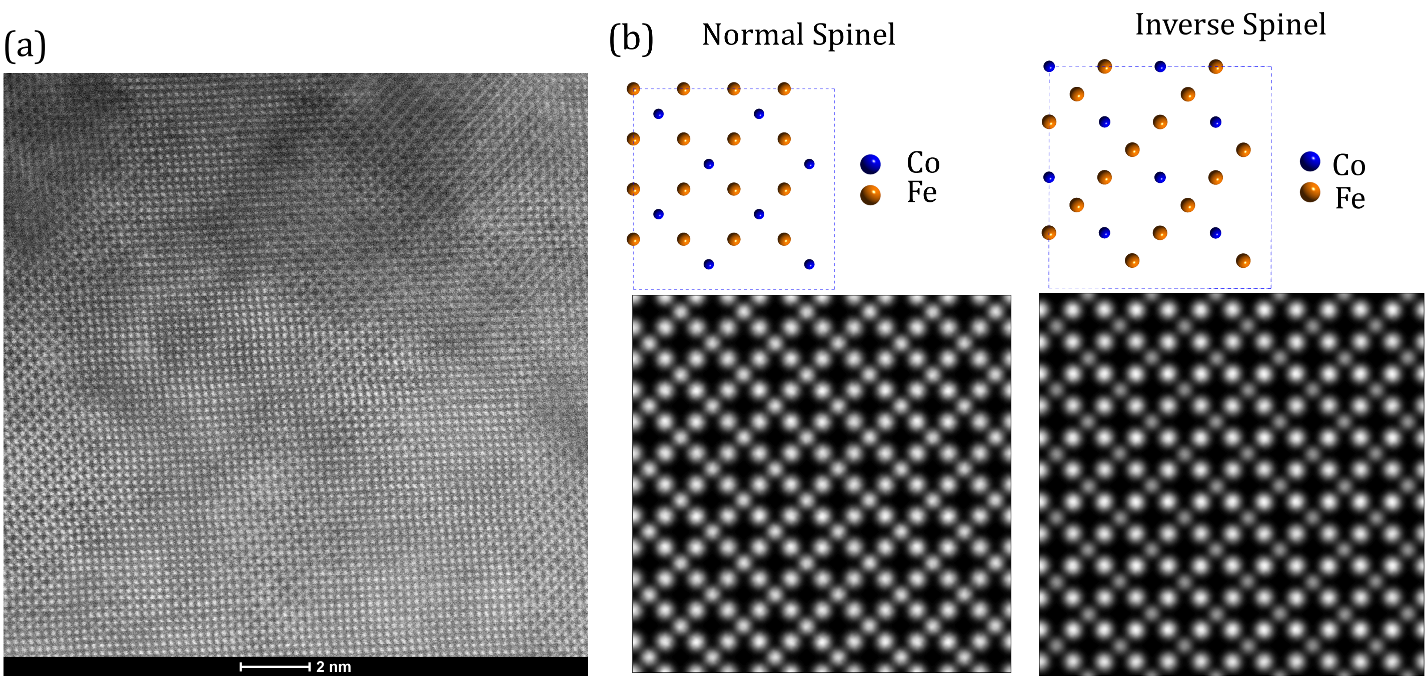

Figure 1. Experimental HADDF image (a) of MBE grown cobalt ferrite. Simulated HAADF images of (b) normal spinel and inverse spinel.

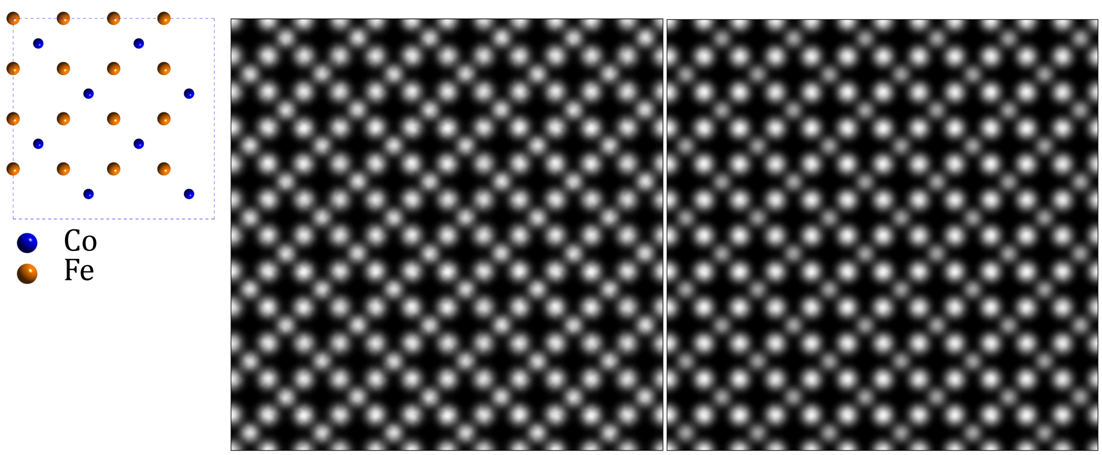

Figure 2. Simulated HADDF images of the same normal spinel structure with different mean square displacement values for the atomic species.

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