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Magnetic Characterization of Isolated CoFeB/Cu Nanowires by Off-Axis Electron Holography

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During the past two decades, one-dimensional (1D) nanomaterials have attracted considerable attention for their important role in miniaturizing electronic devices. In particular, 1D ferromagnetic nanowires (NWs) are of interest due to their unique physical properties and possible applications in magnetic recording, spin electronics, microwave materials and sensor devices [1-4]. Multilayered ferromagnetic NWs, in which the thicknesses of the magnetic and non-magnetic layers can be controlled at the nanometer scale, appear promising [5]. The macroscopic properties of arrays of such NWs are highly dependent on the uniformity of individual NW diameter, composition and crystal structure. A full understanding of the effects of these geometric parameters on the magnetic remanence, effective magnetic anisotropy and microwave permeability of both individual and closely-spaced NWs is crucial for a given application. Here, we study the soft and high-saturation magnetization of periodic CoFeB/Cu NWs as a function of the thicknesses and periods of the magnetic and non-magnetic layers. All NWs were fabricated using pulsed-potential electrodeposition in nanoporous alumina membranes [3].

We use off-axis electron holography (EH) [6] to investigate the local magnetic behavior of a statistical ensemble of ferromagnetic NWs and compared our results with measurements obtained using magnetostatic and ferromagnetic resonance (FMR) of macroscopic NW arrays [3]. We acquire electron holograms at 120 kV using a transmission electron microscope equipped with an electron biprism and a non-immersion Lorentz lens. The results presented below were acquired in a residual magnetic field below 5 Gauss, with the conventional microscope objective lens switched off. Different magnetic states were investigated by applying external magnetic fields to the specimen parallel and perpendicular to the axes of individual NWs. This was done using a combination of specimen tilt and partial excitation of the microscope objective lens, before switching off the applied field and tilting the specimen back to 0 ° to record electron holograms of remanent magnetic states. Mean inner potential contributions to the recorded signal were removed by digitally analysing holograms that had been recorded with opposite directions of magnetisation in the region of interest.

The magnetic induction in CoFeB segments of individual NWs was measured to range from 0.5 to 1.5 T depending on the layer thickness, which ranged between 50 nm and 250 nm. When the magnetic layers were thicker than the Cu layers, the magnetic phase contour lines were observed to lie parallel to the axes of the NWs, with demagnetizing fields visible in the Cu layers. For thinner magnetic layers, a deviation in the direction of the average magnetic induction in individual magnetic layers, away from the NW axis, was observed. This effect is attributed to the aspect ratios of the magnetic segments combined with magnetostatic interactions with neighboring magnetic layers and the direction of the applied magnetic field. Fig. 1 (a) shows an experimental off-axis electron hologram of a CoFeB (50 nm)/Cu (10 nm) NW. Fig. 1 (b) shows the corresponding magnetic contribution to the phase shift, from which mean inner potential contributions to the phase have been removed. The magnetic phase contours are almost exactly aligned with the axis of the NW, with the magnetic return flux visible around each magnetic segment. The average value for the magnetic induction in the CoFeB layers with average thickness of 50 nm is measured to be 1 T.

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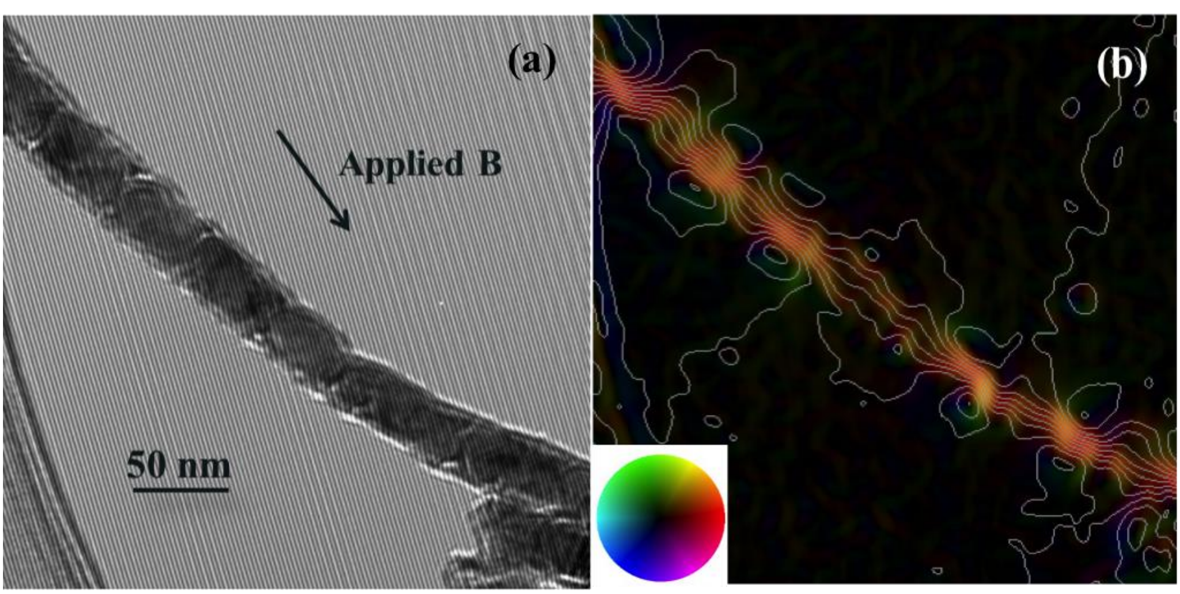

Figure 1. (a) Off-axis electron hologram (acquired at 120 kV) and (b) corresponding magnetic induction map recorded from a CoFeB/Cu (50/10 nm) NW at remanence after applying a magnetic field parallel to the axis of the NW prior to hologram acquisition. Each contour represents a magnetic phase shift of 0.6 radians. The hue and saturation of the colors represent the direction and intensity of the recorded magnetic induction based on the color wheel shown.