Off-Axis Electron Holography of Ferromagnetic Mulitilayer Nanowire Arrays.

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Electrodeposited magnetic nanowires (NWs) have been studied for high frequency applications [1] and for high density storage media [2] due to their relatively low-cost of fabrication and the possibility for the manipulation of their magnetic properties by adjusting the composition and geometric parameters of the array [3]. Multilayer NWs offer additional possibilities for tuning the magnetic anisotropy by controlling the inter-wire distance, and layer thicknesses [4]. However, the magnetization response of magnetic NWs is strongly influenced by the wire diameter and length, inter-wire distance, and wire composition.Therefore, understanding the effects of the geometric parameters of the arrays on their magnetic remanence is crucial if we are to optimize NW for a given application. Here, we have investigated the magnetic and crystallographic properties of single NWs composed of periodic CoFeB/Cu interlayers as a function of magnetic- nonmagnetic layer thicknesses by electron holography(EH) and scanning transmission electron microscopy (STEM) techniques. We investigated the behavior of a statistical ensemble of NWs compared to the magnetostatic and ferromagnetic resonance (FMR) results of bulk NWs .

Multilayer NWs were electrodeposited in a nanoporous alumina membrane obtained by a two-step anodization technique [5]. The average pore diameter and inter-pore distance were 40 nm and 100 nm, respectively, as determined by SEM. The growth of NWs inside the pores by electrodeposition is detailed elsewhere [4]. The NWs consisted of periodic CoFeB(50 nm)/Cu(10 nm), CoFeB(75 nm)/Cu(75 nm) and CoFeB(9 nm)/Cu(3 nm)/CoFeB(9 nm) disk-shaped trilayers separated by thick layers of Cu (50 nm). The layer thicknesses were estimated based on the known electrodeposition efficiency of CoFeB. Individual wires were collected on holey carbon-coated copper grids by dissolving the nanoporous alumina in either nitric acid (HNO_3) or phosphoric acid (H_3PO_4).

Fig 1. (a) and (b) show a bright field TEM (BF) and STEM images, respectively, of a CoFeB(50 nm)/Cu(10 nm) nanowire . The multilayers are not obvious in the BF image since there is little difference in lattice spacing between the CoFeB and Cu layers that would cause diffraction contrast . In comparison, the STEM image shows the existence of multilayers consistent with the expected structure. STEM images are sensitive to atomic mass variations. The wire sides are not atomically smooth. From energy dispersive x-ray elemental maps (not shown) Co and Fe distributions are observed in the darker regions of the wire while Cu dominates the lighter regions, and O is present on the surface of the wire. STEM images also show that the surface porosity of the alumina membranes varied between 10 and 20%, and that the wires were several microns long.

For acquiring holograms, the samples were magnetized with a positive field of +4730 Oe and a negative field of -2015 Oe using the objective lens of the microscope, after tilted the sample +30 deg [6]. After applying these fields, the objective lens was turned off and the sample was set to a tilt angle at 0 deg. Holograms were acquired at remanence (< 5 Oe). Since a biprism voltage of 140V and a magnification of 42000 x were used in Lorentz mode on average, the holographic fringe spacing was 2.5 nm, implying that the average magnetic resolution is 7.5 nm. The magnetization inside the wires is uniform and follows the shape of the wires. The wires have a relatively large magnetization. The weaker magnetization at close to the surface compared to the center is a result of the presence of residual alumina.

For each type of nanowire, magnetization components parallel and perpendicular to the applied field were measured by EH as a function of the angle between the applied field and the nanowire's axis. For 0 and 90 deg, in some cases, the magnetization component transverse to the applied field was observed for the arrays, not the case for magnetization of the bulk samples. This suggests that the easy axis of each magnetic layer is not in the same direction of the adjacent one.

Figure 1.(c) and (d) show a hologram of a CoFeB(50 nm)/Cu(10 nm) wire in Lorentz imaging mode and the magnetic contour map of the same area of the wire after reconstruction of plus and minus 30 deg tilt holograms (the axis of the wires is almost parallel to the applied magnetic field). As seen in Fig 1. (d), in the regions where we have Cu, the magnetic induction becomes weaker as a result of demagnetizing of the field in the non magnetic layers. As mentioned before, the magnetization direction inside the wire has an angle with respect to the axis of the wire.

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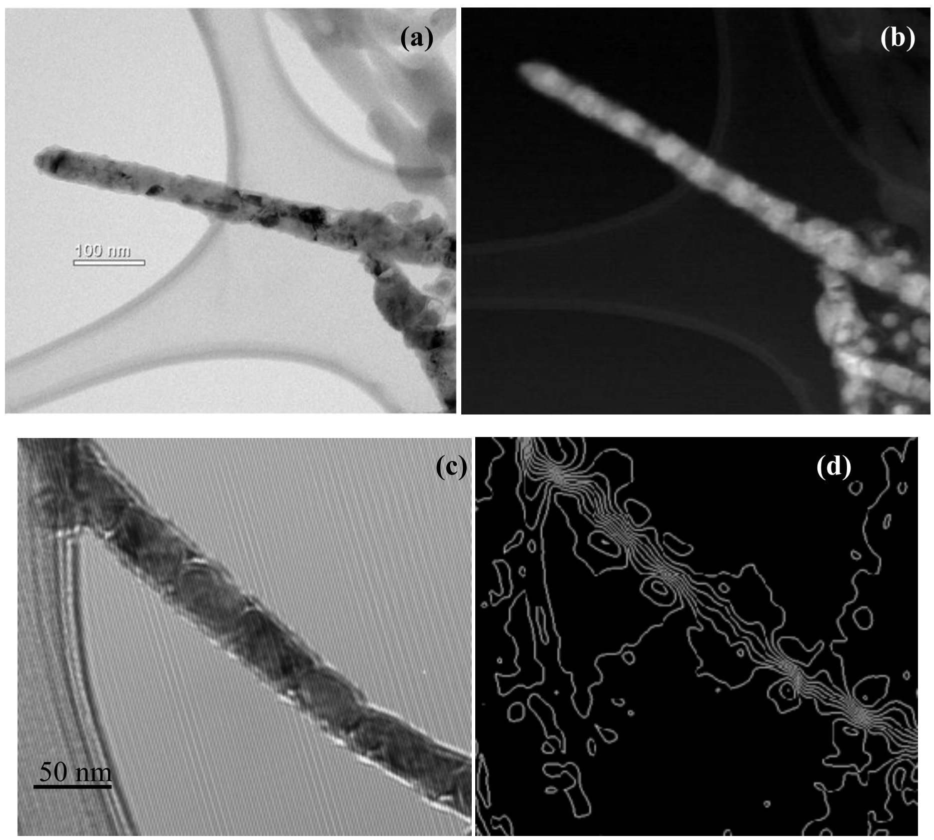

Figure 1.(a) BF and (b) STEM images of a CoFeB(50 nm)/Cu(10 nm) multilayer nanowire. Fig 1.(c) is a TEM image of the same type of sample in Lorentz imaging mode and (d) magnetic contour map of the same area of the wire in (c).The contour spacing is 0.6 radians.