Electrical and magnetoresistance properties of individual NiFe/Pt multilayer nanowires measured *in situ* in a scanning electron microscope

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Electrical and magnetic properties of nanostructured materials have been widely investigated in the last decade due to their applications in electronics [1], optical devices [2] and sensors [3]. Nanostructured materials such as nanowires and nanotubes can exhibit interesting electrical and magnetic properties due to their restricted size and increase in interface density. However it can be a challenge to measure the functional properties of *individual* nanowires due to the difficulties of connecting electrodes to such small structures. Here we measure the magnetoresistance of individual multilayer nanowires *in situ* in SEM using movable electrodes attached to nanomanipulators and an *in-situ* electromagnet.

Magnetic NiFe/Pt multilayer nanowires have been successfully fabricated by pulse electrodeposition into the channels of porous anodic aluminum oxide (AAO) templates, and characterized at the nanoscale. High purity aluminium samples (99.999%) were used as substrate materials to fabricate AAO templates with ~50 nm pore diameter using a one-step anodization process. For the electrodeposition of nanowires, a single bath solution was used to deposit the Pt and NiFe layers containing 90 g/l $NiSO_4$, 13.5 g/l $FeSO_4$, 5 g/l $PtCl_4$ and 30 g/l H_3BO_3. The multilayered structure of the NiFe/Pt nanowires was electrodeposited by switching between the deposition potentials of the two materials with period times of −1.4V for 2 s to deposit NiFe followed by −0.4V for 3 s to deposit Pt. Individual nanowires have uniform structure and regular periodicity. The nanowires were dissolved from the template using 2M NaOH. The NiFe and Pt layers are polycrystalline, with random orientation fcc lattice structure crystallites and grain sizes 3–10 nm [4].

The electrical and giant magnetoresistance (GMR) properties of individual NiFe/Pt multilayer nanowires have been measured *in situ* by nanomanipulators in a scanning electron microscope. Two sharp conductive nichrome probe tips were used as electrodes and prepared using the electrochemical etching method in an electrolyte solution of 1 M NaCl [5]. The electrical resistance of the electrodes tip–tip contact and the circuit containing the individual NiFe/Pt multilayer nanowire were measured as shown in Figs. 1(a) and 1(b). The current–voltage (*I*–*V*) curves of the nichrome tip–tip (R_t) and tips–nanowire (R_C) circuits are linear (Fig. 1(c)), where R_t and R_C are represented by the solid red and dotted blue lines in figure 1(c) respectively. The electrical measurement of ~50 nm diameter individual NiFe/Pt multilayer nanowires shows that the nanowires have a resistivity of ~2.2×10^{-7} Ω m and average resistance of individual NiFe–Pt interfaces of ~0.2 Ω [5].

The GMR effect of the magnetic NiFe/Pt multilayer nanowires was measured in the current perpendicular to plane (CPP) geometry by passing current along the nanowire axis. The CPP-GMR measurements of individual NiFe/Pt nanowires with layer thickness t_{NiFe} = 30nm and t_{Pt} =9nm (Fig.2 (a)) were carried out using a new technique for *in situ* GMR measurement in a SEM. Two magnetic coils were constructed separated by 2 mm gap as a source of controlled magnetic field within the SEM chamber (Fig.2 (b)). Nanowires were then positioned within the electromagnetic gap, and electrical measurements made on an individual nanowire at variable magnetic field. From the data recorded of the CPP-GMR effect of individual NiFe/Pt nanowire for fields up to ~500 Oe, the GMR% measured in a magnetic field applied perpendicular to the wire axis was found to be ~6.14% (Fig.2(c)) and parallel to the wire axis was ~5.6% (Fig.2 (d)) [7].

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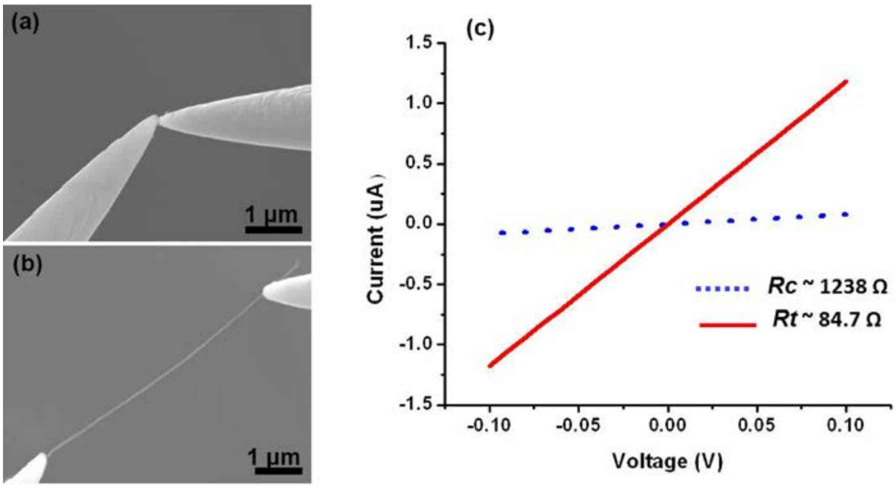

Figure 1. *SEM images of the nanoscale electrical contact of (a) nichrome tips and (b) tips–NiFe/Pt nanowire. (c) I–V behavior of the tip–tip circuit (solid red line) and tips–NiFe/Pt nanowire circuit (dotted blue line).*

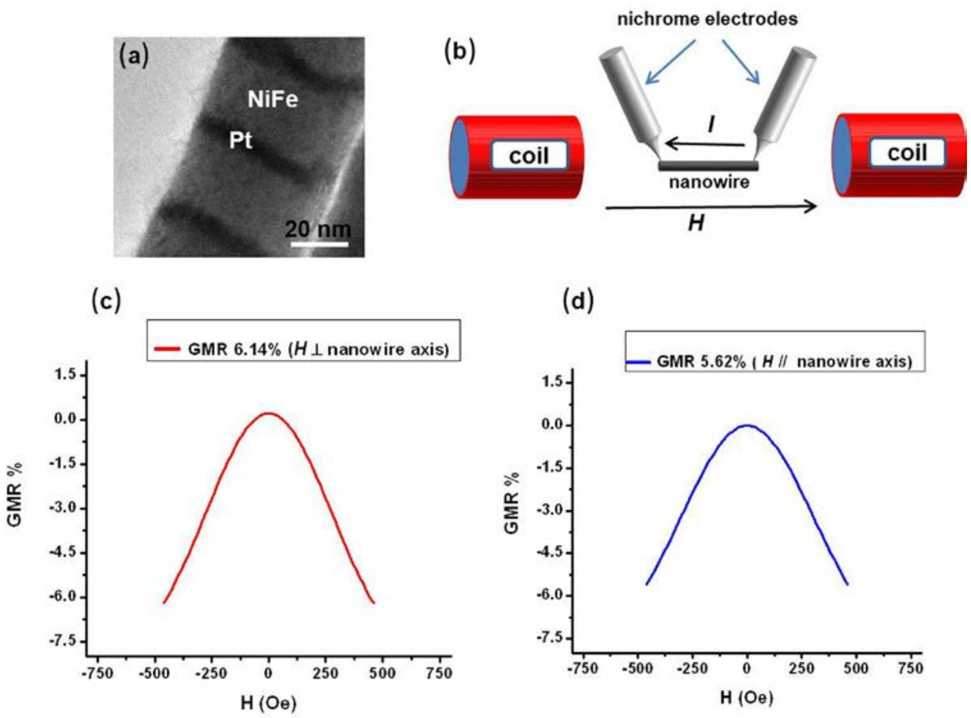

Figure 2. *(a) TEM image of NiFe/Pt multilayer nanowire, (b) Schematic of the GMR measurement system for individual nanowires. GMR effect of individual NiFe/Pt nanowire versus applied field perpendicular to the wire axis (c) and parallel to the wire axis (d).*