Ultra-dense array of single-crystalline cobalt nanowires

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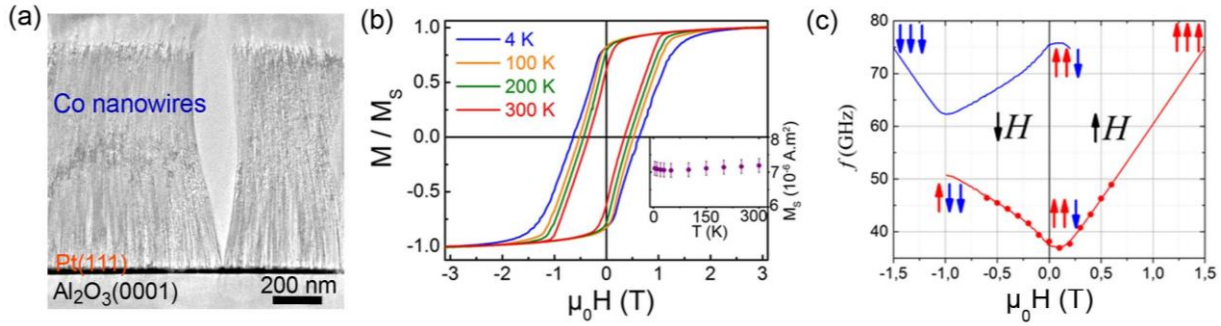
Up to now, ferromagnetic nanowires (NWs) were mainly synthesized by electrodeposition of metals in nanoporous templates resulting in polycrystalline NWs of relatively large diameters and packed at moderate densities. Recently, we reported the epitaxial solution growth of single-crystalline *hcp* Co nanowires of 6 nm in diameter. Without any template, they grow vertically on a un-patterned 1×1 cm^2 Pt(111) film (Fig.a), are spontaneously arranged in hexagonal arrays of 10^{12} NWs/cm^2 and present a perpendicular anisotropy at room temperature [1]. These properties confer a high interest of this system in future ultrahigh magnetic recording.

We present here a detailed magnetic study of such a Co NW array in terms of coercivity, dipolar interactions and magnetocrystalline anisotropy. Despite important dipolar interactions, a high perpendicular anisotropy (*i.e.* parallel to the wires) is obtained due to the combination of the Co *hcp* magnetocrystalline and shape anisotropies which both act along the wire axis: at 300 K, the anisotropy is K_{eff} = 2.4×10^5 J/m^3 with a coercive field $\mu_0 H_C$ = 0.35 T and remanence value *Mr/Ms*=0.61 (Fig.b). This coercive field reaches 0.62 T at 4 K, without any Co/Co oxide exchange bias effect after field cooling. This demonstrates that the chemical synthesis produces intrinsically oxygen free Co nanowires. Contrary to electrodeposited nanowires, the measured temperature dependence of Hc cannot be explained by the Sharrock formula deduced from Stoner-Wohlfarth and Néel-Brown models. On the other hand, the angular dependence of H_C suggests a coherent rotation of the magnetization. The easy axis hysteresis loops are sheared due to dipolar interactions (Fig.a) with a M(H) slope related to the demagnetizing field of the assembly. In this system, the demagnetizing factor is expected to be the array packing fraction P. We found a good agreement between the demagnetizing field slope and P=0.38 determined by small angle neutron scattering. Also, ferromagnetic nuclear resonance (FNR) measurements indicate a shift in the Co spectra related to the assembly demagnetizing field, here also in accordance with the measured packing fraction. In an alternative approach to understanding the anisotropy in this system, we used ferromagnetic resonance (FMR). We observe unusually large resonance frequencies (40 GHz at remanence) and resonance fields (2.3T hard-axis saturation field) which we attribute to an enhanced magnetocrystalline anisotropy. By modelling the dipolar interaction in the array, we could indeed reproduce the resonance positions (Fig.c) assuming a uniaxial anisotropy with first and second order constants K_1=750 kJ/m^3 and K_2=150 kJ/m^3, two values that are about 50% larger than those of bulk *hcp* cobalt. High-field magnetic torque measurements confirm this behaviour and give comparable values. This enhancement of the magnetocristalline anisotropy is discussed in terms of magneto-elastic effect and/or surface anisotropy.

References

[1]. N. Liakakos, *Nano Lett.* **14** 3481 (2014)

Figures



(a) TEM micrograph of a Co NW array grown on Pt(111)/Al_2O_3(0001). (b) Magnetic hysteresis loops measured for a magnetic field applied along the NW, *i.e.* the easy axis of magnetization. (c) FMR resonance frequencies as a function of the applied DC magnetic field (dots: measurements, lines: model).