Template-based Synthesis of 1D Magnetic Nanostructures: Electrodeposition and chemical Methods

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1) Self-ordered and perfect ordered ferromagnetic Nanowire Arrays

In recent years nanomagnet arrays have attracted a lot of scientific interest due to their potential application for perpendicular patterned magnetic media. Using interference lithography C.A. Ross et al. [1] has obtained large scale arrays of nickel columns, which have an aspect ratio of up to 2.5 (column length/diameter).

Self-ordered porous alumina is very suitable template for the fabrication of nanomagnet arrays, in order to achieve magnetic columns with large aspect ratios (>10). Up to now these magnetic arrays exhibits a so-called 2D polycrystalline arrangement of the nanowires and have a deviation of the nanowire diameter of about 10% or even more [2,3]. In this paper, the fabrication of Ni nanowire arrays based on imprint lithography will be presented, which show a perfect hexagonal arrangement on a cm^2-scale. Additionally, we will analyze the influence of the ordering degree of the Ni nanowire arrays on its magnetic properties, i.e. coercivity and squareness.

For the sample preparation, polished Al substrates were patterned by an imprint mold developed [4] in house and consisting of a hexagonal arrays of Si_3N_4 pyramids with 500 nm-pitch (Fig. 1**(a)**). The imprinted etch pits on the Al surface act as initial sides for the pore formation (**b**). The prestructured Al surface was anodized with 1 wt.% phosphoric acid at 195 V for 75 min and an alumina templates (**c**) with a perfect hexagonal arrangement for the pore channels on a cm^2-scale was obtained. Subsequently, the thickness of the barrier layer at the pore bottom was thinned (**d**) from about 250 down to less than 7 nm, which results also resulted to the formation of small dendrite pore at the pore bottom. Nickel was directly plated onto the nearly insulating barrier by current pulses (**e**) and nearly 100% pore filling was obtained. Subsequently, Si substrates were fixed on top of the area **(f)**, the Al substrate was selectively removed by chemical etching and the sample was turned upside down **(g).** Finally, the barrier layer and the dendrite part of the nanowires were removed by sputtering

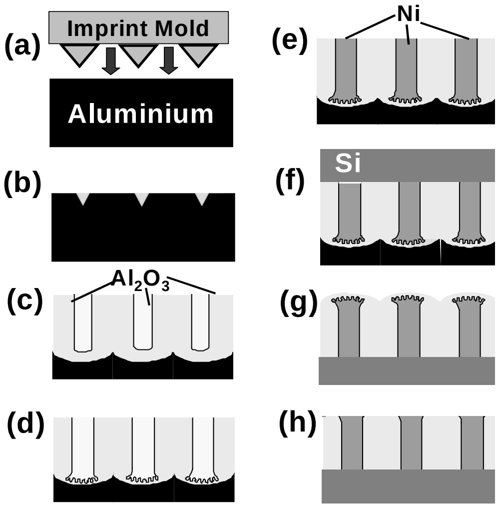


Fig. 1: Preparation steps for fabrication nickel nanowire arrays embedded in an alumina matrix and fixed to a Si substrate

with a focused ion beam **(h),** in order to reduce the stray field interactions between the nanowires.

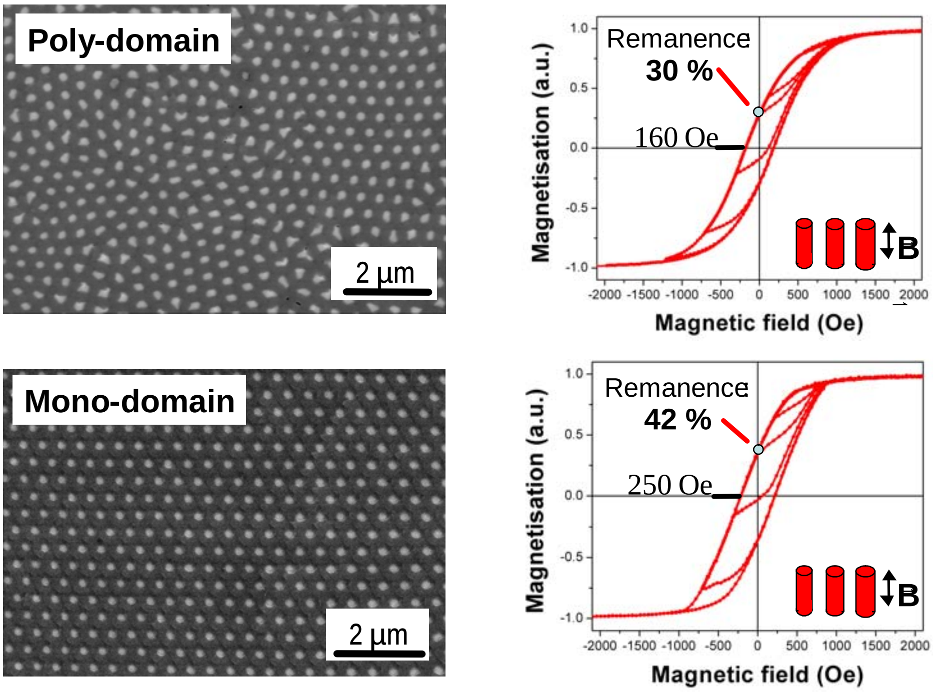


Fig 2: SEM micrographs of nickel filled alumina templates fabricated via imprint lithography and via self-ordering and the corresponding hysteretic loops.

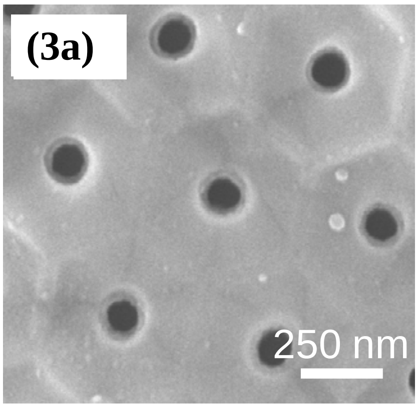
Scanning electron micrographs (**Fig. 2** (lower left image**)**) of the nanowire structures revealed a wire length of about ~4 µm, column spacing of 500 nm, and column diameter of 180 nm with a deviation of less than 2%. In comparison, a Nickel nanowire arrays with 2D-polycrystalline arrangement (**Fig. 2** (upper left image)**)** of the nanowires is also shown. Instead of imprint lithography, a two step anodisation process based on the Masuda approach [3] was used. This nanowire array has a short range ordering and a larger deviation of the nanowire diameter (~12%). Nevertheless, both samples were fabricated under the same electrochemical conditions.

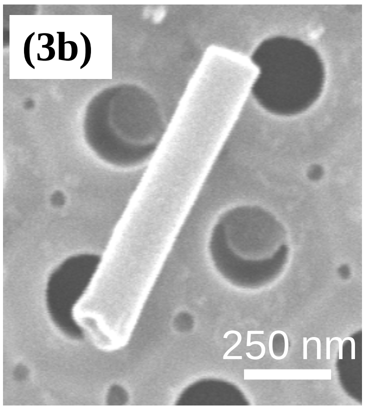
The hysteresis loops were measured for both samples in the direction of the nanowire axis. In the case the nanowire have a monodisperse pore diameter and the nanowire are arranged monocrystalline, a coercive fields of 250 Oe and a squareness of 0.42 was detect. Due to larger dipolar interaction in the nanowire array, based on the larger deviation of the nanowire diameter and the higher disorder of the magnetic array, the second sample exhibits a reduced coercivity of 160 Oe and a squareness of 0.3.

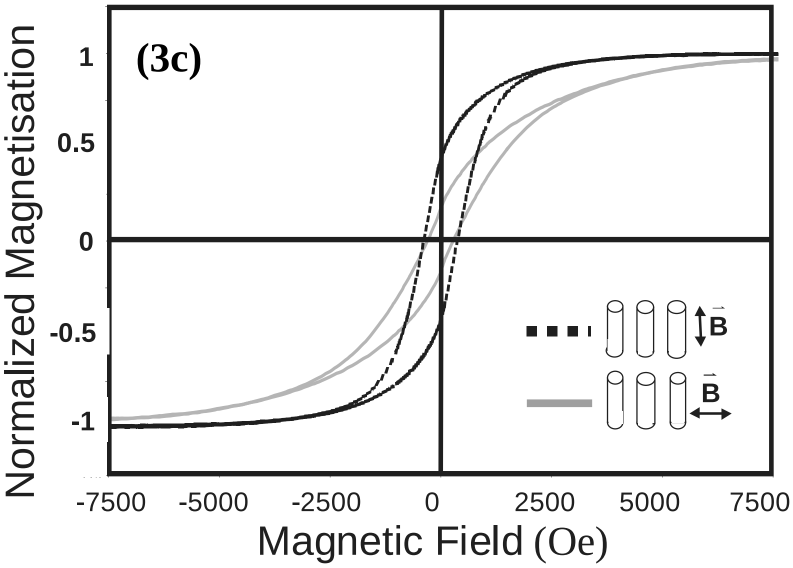
2) Composite Cobalt/Polymer Multilayer Nanotubes

Magnetic nanowire and nanoparticles are nowadays being considered for a broad range of applications ranging from magnetic storage to biotechnology. Magnetic nanotubes are a new class of these structures and have been recently proposed [5] for MRAM devices.

In the present work we report on a novel approach for the fabrication of ferromagnetic nanotubes and present results concerning the magnetic properties of Co nanotubes [6,7]. The surfaces of the pores in self-ordered porous alumina membranes are wetted with a polystyrene or poly-l-lactide layer containing a metallo-organic precursor. Decomposition of the precursor leads to the formation of thin-walled magnetic tubes with diameters of 160 - 450 nm and wall thicknesses of a few nm. During an annealing process for 1 to 3 days at 180 C, a cobalt thin-film forms at the oxide pore-wall/polymer interface. Fig 3a shows an array of cobalt/poylmer nanotube embedded in an alumina membrane with an intertube distance of 500 nm. The thickness of the polysterene layer is 30 to 40 nm and thickness of the cobalt layer is less than 3 nm. After removing the inner polymer tube and an KOH-etch single Cobalt nanotubes can be found on top of the membrane structure. As an example, a single Co nanotube with a diameter of 160 nm and a length of nearly 1µm is shown in Fig. 3b. Room temperature magnetic measurements (see Fig. 3c) clearly show that the tubes have a lower saturation field parallel to their axes, while the in-plane direction is a harder axis. The magnetic properties on varying the wall thickness of the nanotubes will be discussed, and related to the possible micromagnetic configurations such as vortex states that could exist in tubular structures. This project was performed in collaboration with the group of Prof. C.A. Ross group (MIT).







3) Pseudo-Spin-Valve Antidot Arrays

The magneto-transport properties of Pseudo-spin-valve (PSV) thin film structures grown onto sub-150 nm 2D-polycrystalline porous alumina templates have been investigated. Hexagonal and quadratic pore arrangements were achieved by defining a grid in silicon substrates using a combination of interference lithography and reactive ion etching. An alumina layer was then sputter deposited and anodized, resulting in large area porous structures with interpore distance of 180 nm (quadratic lattice) and 208 nm (hexagonal lattice) and a pore diameter ranging from 80 to 150 nm.

The magnetic properties of antidot arrays have recently attracted considerable attention . PSV antidot arrays were fabricated by depositing NiFe/Cu/CoFe thin film structures onto the above mentioned porous alumina templates in a sputter system with a base pressure below 5×10^{-9} Torr. The room temperature hysteresis loops of the antidot structures show the distinct switching of both soft and hard magnetic layers, as well as a significant shearing of the loop, as compared with that of the PSV thin film structure. We have seen that the magnetic properties of antidot arrays are very different from those of continuous [8]. For instance they show an in-plane anisotropy resulting from the presence of the hole array (Fig. 4). The complex magnetization reversal exhibited by these structures is analyzed using micromagnetic simulations. Magnetic anisotropies induced by the different arrangements and dimensions of the pores will be discussed.

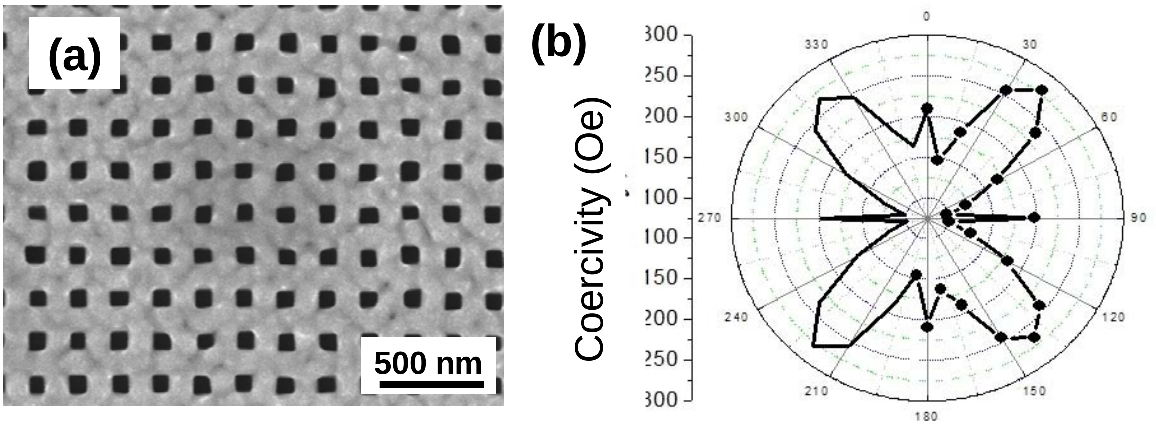


Figure 4: (A) 10nm thick CoFe ‘antidot array ’has been sputtered onto a porous alumina substrate with a square array of holes. **(b)** The coercivity varies with angular direction as a result of the square hole pattern.

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