Single Particle Per Bit Magnetic Information Storage

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Magnetic disk drive technology has successfully reduced the size of multi-grain bits to ~30 nm 30 nm × 100 nm across, and there are intensive industrial efforts to shrink the bit size further. At the same time, there has been great interest in patterned media, where arrays of isolated magnetic marks are read and written individually. This reduces the noise, but lithographic fabrication costs are extremely high. The overall goal of this NIRT project is to demonstrate a new single particle per bit recording paradigm using current-induced switching, which combines the advantages of patterned media, and the potential for lower manufacturing costs in self-assembled nanostructures.

During the first year our main objective has been to prepare patterned media by "nanomasking", in which nanometer-sized magnetic pillars prepared by ion milling of a self-assembled nanoparticle array to transfer the pattern into an underlying thin film. The approach has focused on the underlying science of preparing self-assembled arrays on metallic surfaces and understanding ion milling on the sub-10 nm length scale. The main target here was to demonstrate the ability to transfer the pattern of the array into the thin film below it.

The nanomasking approach takes advantage of self-assembly to prepare patterns on a length scale much smaller than can be achieved with electron beam writing, and it is a massively parallel, rather than serial, fabrication process. The change in the surface morphology expected from ion milling is schematically illustrated in Figure 1. To accomplish this, self-assembled nanoparticle arrays must be prepared on or transferred to magnetic multilayers. While large area highly ordered nanoparticle monolayers can be transferred to amorphous carbon-coated substrates (Fig. 2 a), the wetting behavior of metal surfaces is quite different. We have found that when the magnetic multilayer was terminated with a thin Pt layer, successful transfer could be achieved using the Langmuir-Shaefer method (Fig. 2b).

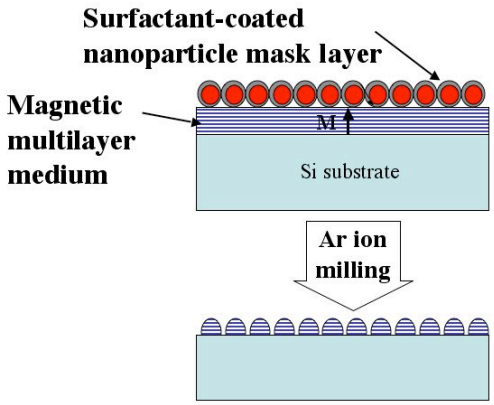

Fig. 1. The nanomasking process: (a.) a crystallographically oriented magnetic multilayer structure (here Co/Pt) is grown on a Si substrate; (b.) a self-assembled nanoparticle array (here 8 nm Co or Fe_3O_4) is transferred to the metal surface by the Langmuir-Schaefer method; (c.) UV irradiation to removes the organic surfactant (gray), so that gaps appear between particles but the order is preserved; and (d.) argon ion milling transfers the pattern of height variations into the underlying multilayers.

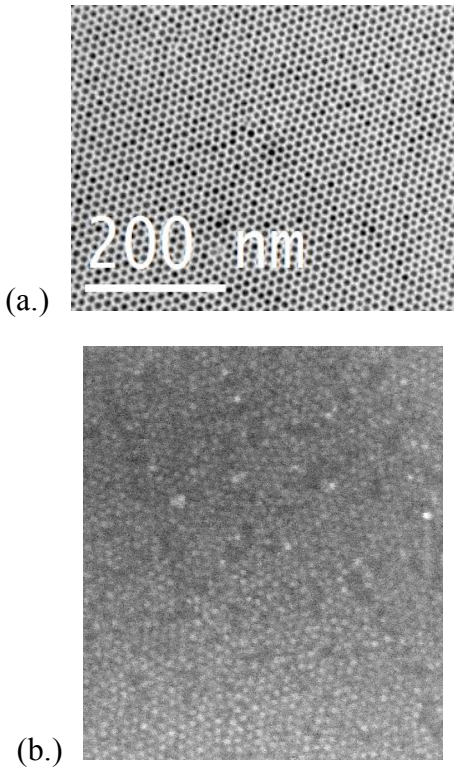

Fig. 2. (a.) Transmission electron microscopy (TEM) image of a monolayer array of cobalt nanoparticles on a carbon-coated TEM grid. Each particle is ~ 8 nm in diameter and has an edge-to edge separation of approximately 4 nm.[1] (b) High resolution scanning electron microscopy (HRSEM) image of a similar array after Langmuir-Schaefer transfer to a magnetic multilayer. The adhesion of the floating particles to the Pt capping layer is not yet optimal, and vacancies are more common. However, most of the array is being transferred.

The pattern of the nanoparticle cores must then be transferred into the underlying multilayers. In the case of magnetic materials, unlike with silicon, there are no suitable reactive etchants that yield gas phase species, and therefore ion milling was used. In this process high-energy argon ions bombard the substrate and knock out atoms. It is well understood for pattern transfer on macroscopic scales, but much less is known about the process on the nanoscale. The ion milling efficiency is fairly insensitive to atomic number, and so removal of the surfactant coating of the nanoparticles prior to milling is important. Otherwise the sample surface appears to be nearly flat, which has been seen in atomic force microscopy images of the Langmuir monolayers of nanoparticles. Experimentally we find comparable milling rates for surfactant coated nanoparticles and pure surfactant --- roughly 6 nm/min at argon ion accelerating voltages of 500 V and current densities of 1 A/m^2. However, significant variability results from variations in the amount of excess surfactant on top of the particles. Samples are now pre-treated with UV irradiation in air (185 nm and 254 nm) to remove the organic coating prior to milling. This also prevents the particles from moving closer together during the milling process, which heats the sample sufficiently to melt the surfactant. Preliminary results from this process are promising. There is no evidence of particle mobility of the surface after the ultraviolet radiation treatment (Fig. 3a). When this region is re-imaged after 90 seconds of milling, no contrast is evident in the region containing arrays of 5-6 nm particles, but the 13-14 nm particles are still present (Fig. 3b). TEM contrast is dominated by the much higher atomic number of iron, relative to that of silicon in the substrate. HRSEM characterization, which is more sensitive to surface topology, is underway in order to determine if the pattern has been transferred under these milling conditions.

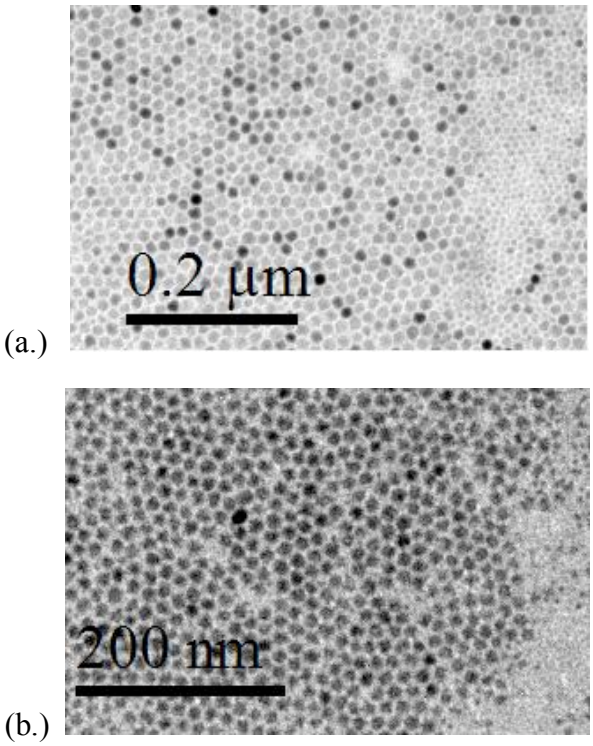

Fig. 3. (a.) TEM image of an evaporated monolayer of a mixture of large (13-14 nm) and small (5-6 nm) Fe_3O_4 nanoparticles, on a SiO_x-coated TEM grid. The particles of different sizes segregate and form ordered regions with particles of similar size. This image was taken after 2 hrs of UV exposure, and shows that no gaps have opened up, which happens if the sample is heated to remove the surfactant coating, because the particles are then mobile and can pack more closely together; (b.) After 90 s of argon ion milling (500 V, 20 mA).

While the nanomasking process was being optimized, we also made larger structures using conventional photolithography and electron beam lithography to examine the defect density in magnetic multilayer structures. Our model system for the nanomask pattern transfer has been Co/Pt multilayers with large grains. Care has been taken with these films to make them as magnetically homogeneous as possible, with a coercivity dominated by domain wall motion through the films. Thus, the films have relatively low coercivity, and we assume nucleation of reversed regions in the films is not needed in order to switch them. These pre-nucleated switched regions are assumed to exist in a random array within the film.

The pattern size was varied, and correlated with the magnetic switching field distribution. As the grid size approached the mean spacing between the nucleation sites, many of the patterned grids no longer contain a nucleation site. In this case, these grids will see large increase in coercivity set by the need to nucleate a reversed region without an assisting defect. By studying what fraction of the films sees an increase in coercivity as a function of grid size it was possible to extract the average spacing of nucleation sites, and therefore defects in the magnetic structure. Initial measurements on samples patterned with 8 μm grid size show an increase in coercivity for about half of the squares, which suggests a mean separation between nuclei of around 10 μm.

References

[1] For further information about this project link to http://www.andrew.cmu.edu/user/sm70/index.html or http://info.phys.cmu.edu/people/faculty/Majetich/ or email **sara@cmu.edu**
[2] M. Sachan, N. D. Walrath, S. A. Majetich, K. Krycka, and C.-C. Kao, *J. Appl. Phys.* **99**, 08C302 (2006).