Programmable Microscopic Magnetic Self-Assembly

CNF Project Number: 2964-21
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Primary Source(s) of Research Funding: National Science Foundation, Alfred P. Sloan Foundation

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Primary CNF Tools Used: Oxford 81/82 etcher, YES EcoClean Asher, ASML DUV stepper, Gamma Automatic Coat-Develop Tool, JEOL 6300 EBL, SC 4500 odd-hour evaporator, AJA Sputter Deposition, Heidelberg DWL2000, PT770 etcher (left side), Unaxis 770 Deep Silicon Etcher, Plasma-Therm Takachi HDP-CVD, Oxford PECVD, Oxford ALD, Zeiss SEM, Veeco AFM

Abstract:

We develop an experimental platform for programmable microscopic magnetic self-assembly. We manufacture these microparticles at the wafer-scale, and have precisely designed shapes, magnetic moments, and magnetic interactions. Once released, we drive particles to explore their configuration space by a rotating magnetic field, generating chaotic flows that mix particles and drive assembly at the air-water interface. As a first example, we control self-limiting assembly by designing the shape and net magnetic moment of clusters at various stages in the assembly process. In particular, we show that spontaneous decoupling of the final product from the reaction forms a powerful principle for self-limiting assembly.

Summary of Research:

Recent progress has been made towards the self-assembly of structures that terminate at a finite size, rather than growing indefinitely. Such structures require a mechanism to detect when a cluster of a specific size is formed, and to prevent larger clusters from growing. Current strategies for such a self-sensing mechanism include geometric self-closing [1], geometric frustration [2], and strain accumulation [3].

Here, we demonstrate a new mechanism for non-equilibrium self-limiting assembly, which relies on programmable magnetic interactions between constituent particles. Our strategy makes use of the fact that the net moment of a magnetically assembled cluster is the vector sum of the constituent moments. We design a cluster which, when assembled, has no net magnetic moment and thus spontaneously decouples from external magnetic driving. This spontaneous decoupling ensures that once a cluster is fully formed, it achieves stability and ceases to interact with the external driving field.

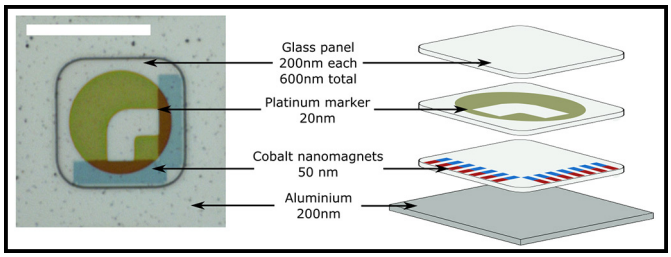

Figure 1: Schematic and optical microscope image of magnetic device layer structure.

Consequently, this halts the cluster's growth at a specific size, while other magnetically driven particles remain actively engaged in mixing and assembly.

Our devices are completely fabricated at CNF (see Figure 1 for device schematic). On top of a aluminum/aluminum oxide sacrificial layer, we pattern single-domain cobalt nanomagnets using electron-beam lithography [4] and metallize by liftoff. These nanomagnets are then embedded in silicon oxide thin films, whose shape and size are precisely patterned by a deep-ultraviolet (DUV) stepper. The combination of photolithography and electro-beam lithography allow us to pattern magnetic devices where the strength and shape of the magnetic interaction, placement of magnets, and contact interactions from the silicon oxide panel can all be harnessed to design a landscape for magnetic self-assembly.

We release these panels and observe their dynamics in the lab under an optical microscope. In order to do so, we deep reactive ion etch through the back of the silicon wafer, leaving only the sacrificial layers and magnetic devices. The magnetic devices are coated with a hydrophobic polymer layer, such that when TMAH solution is added to etch the sacrificial layer, the magnetic devices are released to float on the liquid-air interface.

Surface tension (combined with the hydrophobic particle surface) confines the particles to a single layer, allowing us to record and observe their interactions.

The very low friction environment of the liquid-air interface enables us to visualize the effect of small magnetic forces, as well as to introduce out-of-equilibrium driving. In this case, we use rotating magnetic fields to generate particle rotation. As the particles align to follow the applied magnetic torque, the fluid around them is forced to rotate with each particle. When particles are sufficiently close, these rotating hydrodynamic flows become collectively chaotic, acting to effectively mix particles and "thermalize" the system.

The exact parameters of the magnetic driving control the final distribution of assembly products (see Figure 2 for assembly design, and Figure 3 for distribution of final product as a function of magnetic driving). For example, if particles are consistently driven at a high amplitude (40 Oe) magnetic field, particles remain separated and do not assemble, since the magnetic torque dominates over local interactions that drive assembly. Driving particles at a small amplitude (10 Oe) magnetic field results in disordered aggregation: all products of the assembly are formed in equal proportion, since the magnetic driving is insufficient to thoroughly mix the particles. However, driving magnetic assembly at an intermediate magnetic field (20-30 Oe) produces the maximum conversion into the final assembly product. At this magnetic field condition, particles are able to overcome the applied torque and assemble into higher order products, while also being mixed sufficiently to explore their local environment.

We can further enhance the fraction of successfully assembled final product by dynamically changing the magnetic field driving conditions. This strategy makes use of the fact that the final assembled product spontaneously decouples from the external field, so that raising the magnetic driving to a high amplitude will break incomplete or undesired structures, but not the final product. As a result, cyclically lowering and raising the magnetic field will gradually enhance the number of particles that successfully assemble into the final product (see Figure 4).

This work demonstrates a general design principle for out-of-equilibrium self-limiting assembly by spontaneous decoupling. Future work will leverage these ideas to generate complex structures, particularly those that harness energy from external magnetic fields to perform useful work. Combining these principles with programmable magnetic bindings [4-6] will provide a powerful platform for complex, functional magnetic microstructures.

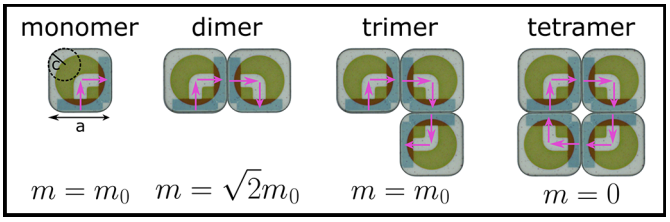

Figure 2: Schematic of assembly products from four identical magnetic devices, with magnetic moments indicated as arrows.

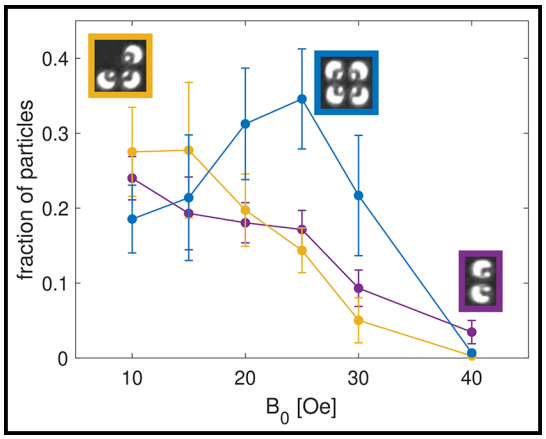

Figure 3: Plot of the distribution of assembly products (dimer, trimer, and tetramer) as a function of the amplitude of magnetic driving. The total yield (including monomer) sums to 1.

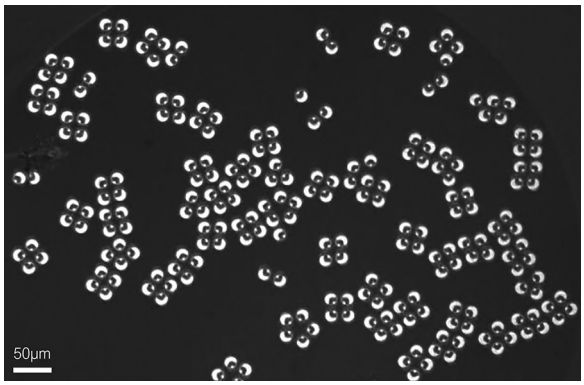

Figure 4: Optical microscope image of the product of several cycles of magnetic cyclic driving, where almost all panels have assembled into tetramers.

References:

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