# Programmable Microscopic Magnetic Self-Assembly


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Primary CNF Tools Used: Oxford 81/82 Etcher, Oxford 100 Etcher, ASML DUV Stepper, JEOL 6300 EBL, SC 4500 Odd-Hour Evaporator, AJA Sputter, Oxford PECVD, Heidelberg Mask Writer - DWL2000, PT770 Etcher, Unaxis DRIE, Plasma-Therm DRIE, Zeiss SEM, Veeco AFM


## Abstract:

**We are developing a microscopic self-assembly system with programmable magnetic interactions. In order to encode specific magnetic lock-and-key interactions between pairs of micron-scale particles, we embed nanoscale single-domain magnets along their perimeters, and program their magnetic configurations. When these non-equilibrium particles are magnetically and hydrodynamically driven to explore their configuration space, they self-assemble into complex structures, as encoded by the embedded magnetic information.**


## Summary of Research:

Self-assembly refers to a group of ubiquitous processes that turns a disordered system of dispersed building blocks into organized structures or patterns via local interactions between the building blocks with minimal external guidance. Among various kinds of local interactions that can lead to self-assembly, the magnetic interaction is unique for its scalability across multiple scales from sub-micrometer to macroscopic. Previously, we have shown that macroscopic polymer particles with embedded permanent magnets can self-assemble via programmable magnetic interactions into 1D polymers, 2D square lattices and even 3D cage structures [1]. Based on the scalable nature of magnetic interactions, we are now developing magnetically programmable particles with information encoded in the magnetic patterns to achieve self-assembly in a controlled manner at the microscale.

We have fabricated microscale panels with magnetic patterns embedded in silicon oxide thin films as building blocks for programmable magnetic self-assembly (Figure 1a,b). Sub micrometer single-domain nanomagnets that are pill shaped and have various aspect ratios are patterned via electron beam lithography followed by metallization of cobalt and liftoff. Since the nanomagnet coercivity is directly controlled by its aspect ratio, we can fabricate domains with small and large magnetic coercivity which allows us to control the domain magnetization through sequential application of large followed by smaller magnetic fields [2]. For instance, in order to have opposite magnetic dipoles in both x and y directions, we pattern two types of nanomagnets with different aspect ratios and coercivities.

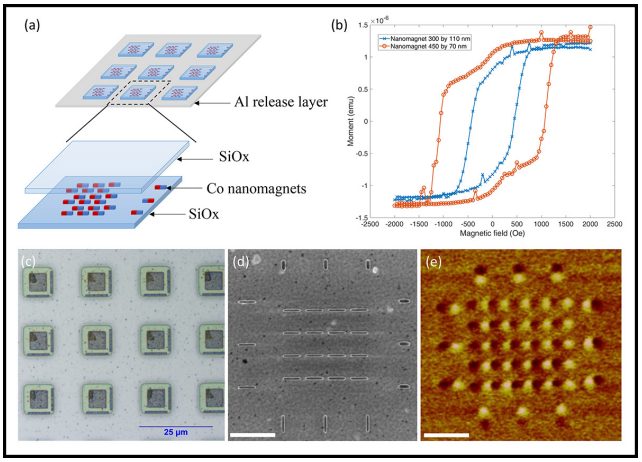


*Figure 1: Magnetically programmable self-assembly at water-air interface. (a-b) schematics and optical image of the magnetic panels. (c-d) SEM and MFM images of the magnetic panels. Scale bar: 1 μm.*

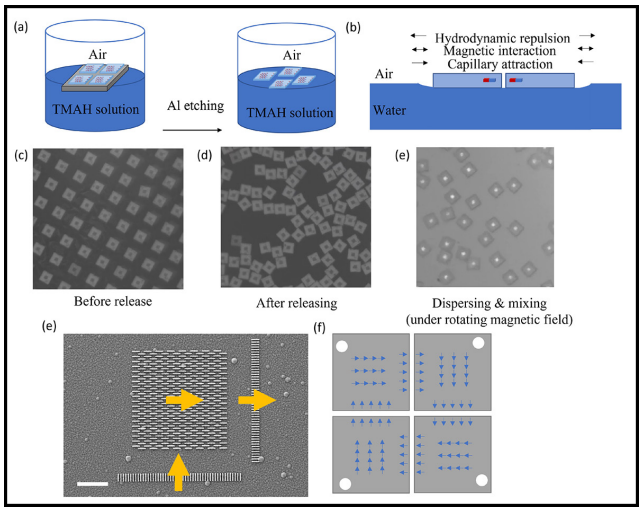


*Figure 2: (a) Schematics of magnetic panels released and assembled at water-air interface. (b-e) Magnetic panels float at the water-air interface before/after releasing and mixing. (f) SEM of nanomagnets pattern for self-limiting assembly. Scale bar: 2 μm. (g) Schematic of a tetramer assembled from four identical magnetic panels.*

All the magnets are first magnetized (in both x and y directions) using a magnetic field higher than the coercive fields for both domains. Subsequently, the shorter domains are magnetized in the opposite directions using a coercive field whose intensity is high enough to flip the short domains but too weak to flip the long domains. In this way, we produce near-field interactions between adjacent magnetic panels with programmable selectivity.

By introducing lock and key pairs of magnetic handshake patterns into the design of patterns, we aim to generate specificity in magnetic bindings [1,3]. Utilizing the specificity of magnetic bindings, we could further design more complex self-assembled structures such as polymers with unique properties and functionalities and even self-assembled magnetic micromachines. Finally, in addition to these near-field interactions, we control the panel far-field interactions by patterning a large central array of magnets (see Figure 1a). This central array of magnets also provides a means to actuate the magnetic panels with an external magnetic field.

The panels are fabricated on a suspended thin sacrificial layer made of aluminum. We release the panels for self-assembly by floating the panels and sacrificial layer on top of a tetramethylammonium hydroxide (TMAH) solution. The TMAH etches the aluminium layer, leaving the magnetic panels free-floating in a single layer, on an effectively frictionless two-dimensional surface (Figure 2a). We design the shape and size of the magnetic panels so as to minimize the distortion of the liquid interface caused by the panels, thus isolating the forces driving assembly to the magnetic patterns on the panel edge.

The very low friction environment of the liquid interface enables us to visualize the effect of small magnetic forces, as well as to introduce out-of-equilibrium driving.

In particular, to allow the panels to effectively explore their configuration space, we spin the panels using a rotating external magnetic field. As the particles spin, the fluid around them is also forced to flow in a vortex. As the spinning speed increases, this rotating flow leads to chaotic trajectories between individual magnetic panels, so that panels “mix” and weak structures break (Figure 2b-d). For sufficiently large rotation rates (more than 10 Hz), the magnetic panels explore their configuration space until they bind in their strongest configuration (Figure 2e).

As the first proof of concept, we demonstrate that a single type of magnetically patterned square panel self-assembles into self-limiting clusters. The magnetic patterns consist of a large central magnet array as the handle for external field manipulation and mixing, and two arrays of magnets near the two adjacent edges of the panels (Figure 2f,g). When the correct binding forms, four panels will be assembled into a tetramer, with each panel rotated 90° from the adjacent one (Figure 2g).

In addition to self-assembly at the water-air interface for 2D structures, we also developed an acoustic approach that could effectively agitate the micrometer-sized particles in 3D (Figure 3a,b). We utilize surface acoustic wave (SAW) devices to generate standing surface acoustic wave (SSAW) on a lithium niobate piezoelectric substrate and then couple the wave into the microfluidic well where the magnetic particles are released (Figure 3a). The particles are manipulated by acoustic radiation force and acoustic streaming. To effectively mix the particles, we further modulate the phase of the voltage signal applied to the interdigital transducers and randomized the distribution of the pressure nodes of the SSAW. We envision that this acoustic agitation approach could be adopted in future self-assembly experiments for programmable 3D assembly of magnetic particles.

## References:

[1] R. Niu, C. X. Du, E. Esposito, J. Ng, M. P. Brenner, P. L. McEuen, I. Cohen, Proceedings of the National Academy of Sciences 2019, 116, 24402.

[2] J. Cui, T.-Y. Huang, Z. Luo, P. Testa, H. Gu, X.-Z. Chen, B. J. Nelson, L. J. Heyderman, Nature 2019, 575, 164.

[3] C. X. Du, H. A. Zhang, T. Pearson, J. Ng, P. McEuen, I. Cohen, M. P. Brenner, arXiv preprint arXiv:2112.02614 2021.

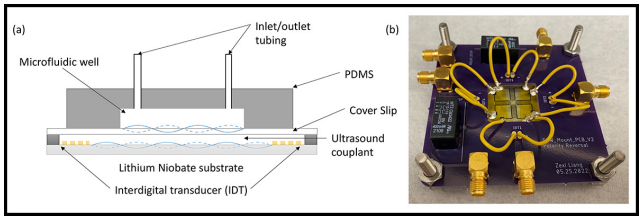


*Figure 3: (a) Schematic of the surface acoustic wave setup for magnetic particle agitation in microfluidics. (b) Photo of the surface acoustic device bonded to the driving circuit board.*