

Magnetic Handshakes for Programmable Microscale Self-Assembly

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Primary CNF Tools Used: Oxford 81/82 etcher, YES EcoClean Asher, ASML DUV stepper, Gamma Automatic Coat-Develop Tool, JEOL 9500 EBL, JEOL 6300 EBL, SC 4500 odd-hour evaporator, AJA Sputter Deposition, Heidelberg DWL2000, PT770 etcher (left side), Unaxis 770 Deep Silicon Etcher, Oxford FlexAL, Oxford PECVD, Plasma-Therm Takachi HDP-CVD, Zeiss SEM, Veeco AFM

Abstract:

We develop a microscale self-assembly platform in which lithographically patterned nanomagnets encode local bonding rules into individual building blocks. The approximately 20 μm silicon-oxide particles contain arrays of single-domain cobalt nanomagnets whose orientation and position form digital magnetic “barcodes.” A global rotating field drives transport and repeated encounters, while the embedded barcodes determine which contacts become stable. Orthogonal multibit barcodes provide selective recognition among as many as 20 particle species, with ten intended partner pairs assembling together in a single bath. At the collective level, changing the external global field can reshape the energy landscape and reconfigure the target structure. Together, local magnetic encoding and global field control provide a fabrication-compatible route to selective and reconfigurable microscale assembly.

Research Summary:

Programmable self-assembly requires building blocks that can identify intended partners and alter their interaction rules in response to an external command. DNA-mediated interactions provide powerful molecular and colloidal specificity, but larger microscale components diffuse slowly and often require stronger, longer-range driving. Magnetic handshake materials offer a complementary strategy in which spatial patterns of magnetic dipoles encode binding information directly into each component (1–2). The global field supplies transport and control, while the patterned nanomagnets determine the local interaction between contacting particles.

Our building blocks are fabricated in parallel on four-inch silicon wafers. A sacrificial aluminum layer

supports multilayer silicon-oxide particle bodies containing optical identity markers and patterned cobalt nanomagnets. Electron-beam lithography defines single-domain magnets with controlled aspect ratios. Shape anisotropy sets both the remanent moment direction and coercive field. By combining two coercivity classes with two orthogonal orientations, four magnet groups can be addressed sequentially using global x- and y-directed field pulses. The resulting magnetization pattern forms a multibit barcode along selected particle edges. After fabrication, dilute tetramethylammonium hydroxide removes the aluminum layer and releases the particles to an air–water interface, where an in-plane rotating magnetic field mixes the population and promotes repeated encounters.

Selective Assembly through Orthogonal Magnetic Barcodes

We encode partner identity using eight-bit magnetic barcodes. Complementary edge patterns produce a strongly attractive interaction, whereas mismatched patterns are designed to be weakly interacting or neutral. The number of mutually orthogonal barcode pairs increases approximately linearly with barcode length, allowing an eight-bit design to support 16 selective pairs. We selected ten of these pairs for experiment, using 20 optically labeled particle species, 20 copies of each species, and 400 particles in a single bath. The designed interaction matrix isolates each intended pair from the off-target combinations. After magnetic mixing, intended dimers dominate the observed products: most pairs reach near-perfect partner-selection accuracy, although assembly yield varies among barcode sequences. The measured results show that local magnetic patterns can encode component identity and selective recognition without individually addressing the particles.

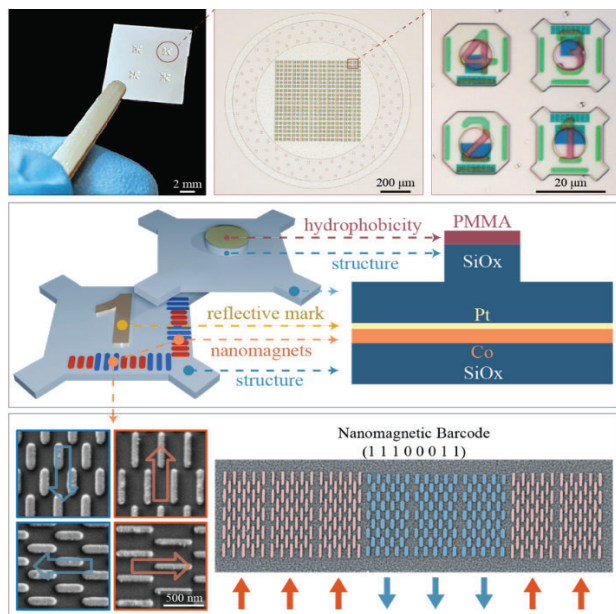


Figure 1: Wafer-scale fabrication of magnetic handshake particles and nanomagnetic barcodes.

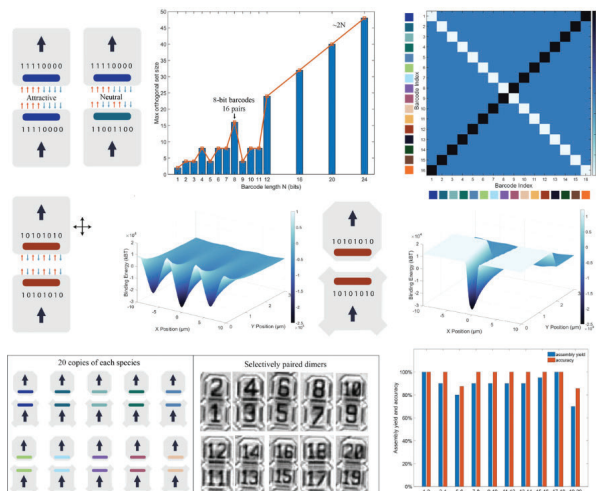


Figure 2: Selective recognition and assembly using orthogonal magnetic barcodes.

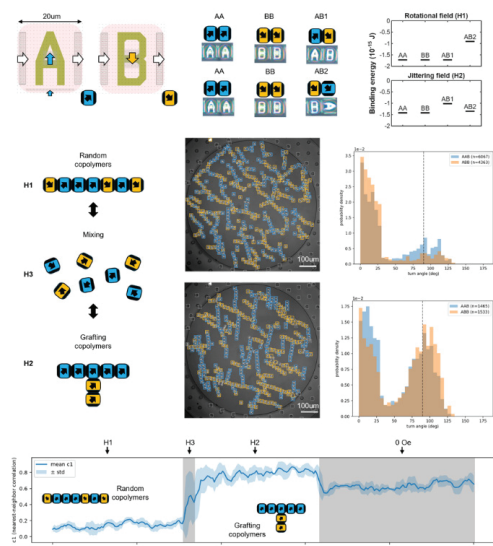


Figure 3: Field-directed rearrangement of chains composed of two types of particles.

Field-Driven Reconfigurability through Energy Landscape

The applied global magnetic field reconfigures the collective energy landscape by changing the relative stability of particle–particle bonding configurations. Under an in-plane rotating field, particles preferentially assemble into predominantly linear, random copolymer-like chains. A brief high-amplitude mixing pulse disrupts these existing bonds, allowing the particles to escape local energy minima and rearrange. Subsequent application of a jittering field stabilizes both linear and approximately 90° bonding configurations, producing branched, graft copolymer-like structures. Turning-angle distributions and nearest-neighbor correlations quantify this transition, demonstrating controllable field-driven reconfiguration between distinct target morphologies without changing the constituent particles.

Conclusions and Future Steps:

Together, the local barcode and the global field provide two complementary levels of control. The barcode specifies which components recognize one another, while the applied field controls the collective energy landscape and accessible target structures. This separation allows many particle species to be actuated together while retaining locally differentiated behavior.

References:

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