Ferrofluid Lithography

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Self-assembly has been proposed as a "bottom up" approach to pattern micro/nanoscale structures with quasi-periodicity [1]. However, existing approaches usually result in a single average spatial period in the entire assembly area, and they do not provide means for active tuning of the period. Here we propose the use of an externally applied magnetic field [2,3] for nanoparticle assembly that is both spatially variant and tunable, and demonstrate preliminary results of lithographic patterning based on field-induced assembly.

The proposed fabrication process is illustrated in Figure 1. A fluid containing magnetic colloidal nanoparticles, also known as a "ferrofluid" [2], is confined over a resist-coated substrate, as depicted in Figure 1(a). In the absence of external fields, the particles are randomly dispersed. If an external magnetic field is applied, the particles aggregate and assemble into quasi-periodic patterns, as illustrated in Figure 1(b). The geometry of the assembly depends on factors such as the strength and direction of the applied field; therefore, the geometry can be actively tuned. The particle/liquid phase separation then provides a periodic modulation of optical transmission, and thus the assembled ferrofluid essentially acts as a tunable lithography mask. UV illumination can then expose the resist; after development, the pattern of the assembled structure transfers into resist, as shown in Figure 1(c-d). Using this process, any field-induced assembly structure can be recorded.

Preliminary field-induced assembly results are shown in Figure 2(a), where the black dots, aggregated iron oxide nanoparticles, form a quasi-periodic array after an out-of-plane magnetic field has been applied. While the assembled structure has low spatial-phase coherence resulting in random orientations, its feature size distribution is confined to a relatively narrow band, as seen in the spatial spectrum that was calculated in the inset of Figure 2(a). By introducing additional constraints, such as a physical template [4,5], we expect to improve the coherence of the assembled structures. We have also shown that a spatially variant externally applied field results in similarly variant period of the assembled pattern. Initial results of ferrofluid lithography using the ferrofluid as a tunable mask are shown in Figure 2(b). The black dots (diameter $d \sim 500$ nm) in the image are unexposed resist patterned due to the presence of nanoparticles positioned by magnetic field-induced assembly, according to the process of Figure 1. The sizes of the patterned dots are fairly consistent, but some structures were washed away because exposure conditions have not yet been optimized.

The purposed ferrofluid lithography is a simple and yet versatile process that exploits field-induced assembly of nanoparticles to fabricate quasi-periodic patterns. Initial results successfully demonstrated patterning of quasi-periodic dot arrays with ~500 nm diameter. We plan to explore ferrofluid lithography to pattern finer structures with higher spatial-phase coherence.

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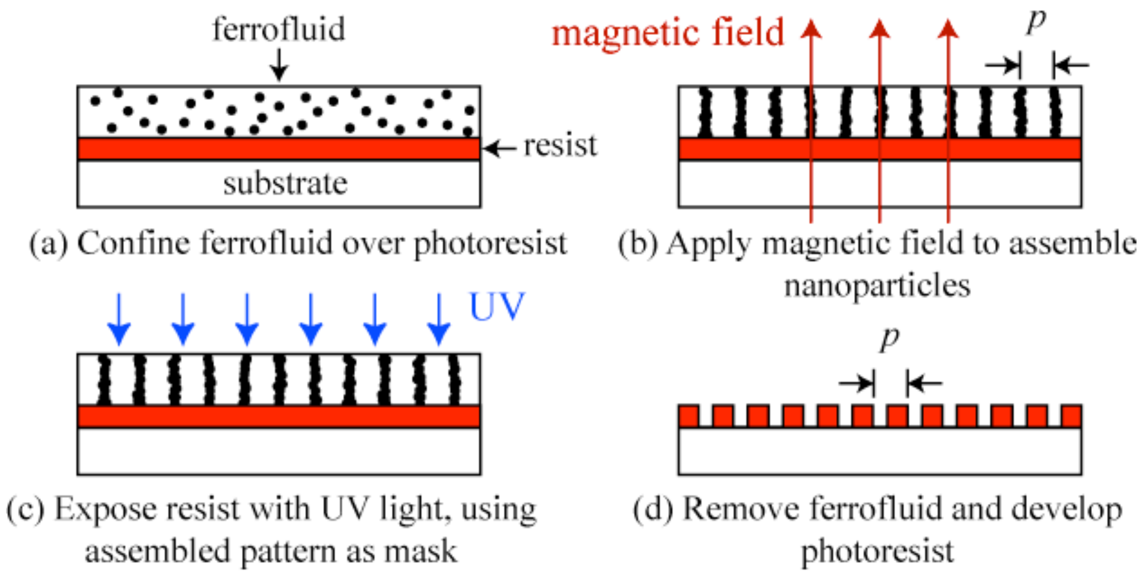

Figure 1 Process flow diagram for Ferrofluid Lithography.

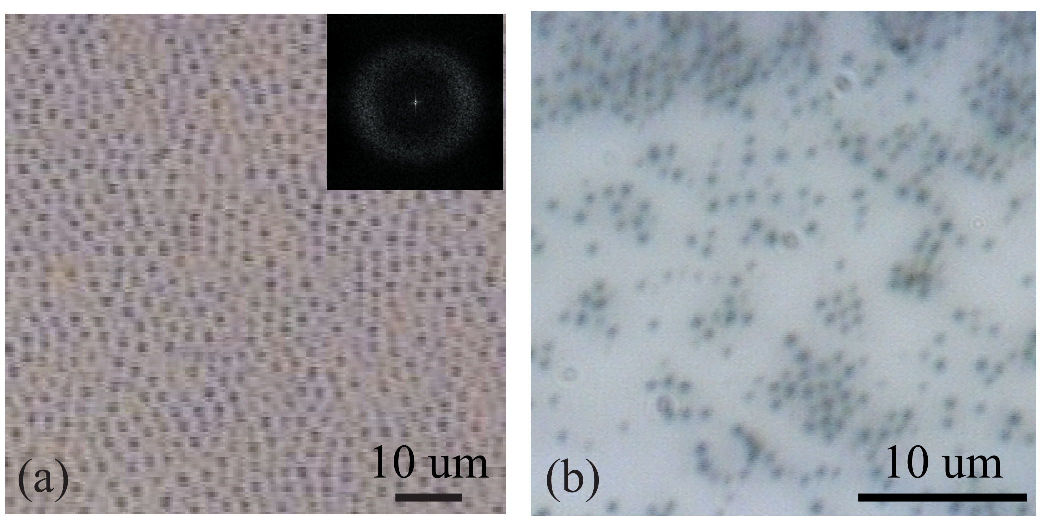

Figure 2 Microscope images of (a) field-induced assembly of nanoparticles in water. The applied magnetic field is out-of-plane. The inset is the 2D spectrum of the image, demonstrating consistent pattern size but random orientations. (b) The dots are unexposed resist patterned by ferrofluid lithography.

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