

Density Multiplication and Improved Lithography by Directed Block Copolymer Assembly for Patterned Media at 1Tbit/in² and Beyond

Summary

Bit patterned media stands out as a potential route to thermally stable data recording at densities greater than 1 Tbit/in² where conventional continuous granular media may not be stable against thermally activated magnetization reversal. In bit patterned media, each magnetic bit is physically patterned onto the disk (Figure 1). At densities greater than 1Tbit/in², the required lithographic resolution must have a full pitch of 27nm and smaller with stringent quality constraints.

The lithographic definition of a bit patterned media template is a significant challenge, especially when considering that the semiconductor industry roadmap is potentially years away from realizing these dimensions. A suitable strategy for patterned media fabrication therefore begins with the generation of a master pattern. We combine block copolymer self assembly with e-beam lithography to direct the assembly of defect-free arrays of block copolymer domains at densities up to 1 Tdot/in² on chemically patterned surfaces. In comparing the assembled structures to the chemical pattern generated by e-beam lithography, the feature density can be multiplied by a factor of four (and possibly higher) and the dimensional uniformity is vastly improved. These results have profound implications for advancing the performance and capabilities of lithographic materials and processes beyond current limits.

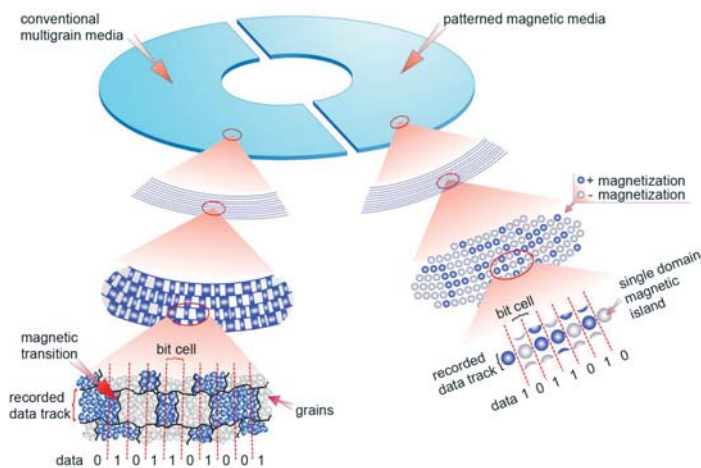


Figure 1: In bit patterned media, each magnetic bit is physically patterned onto the disk.

Introduction

Magnetic recording, invented over 100 years ago, has played a key role in the development of information storage technologies, including analog audio, video and digital data recording. Since the sale of the first magnetic hard disk drive by IBM in 1956, the capacity and storage density, i.e. the number of bits per square inch (bits/in²), have increased dramatically. The increase in density has required continuous scaling in the components of the disk drive to ever smaller dimensions. Ultimately, the recording density will be limited by the onset of thermally activated magnetization reversal or by the inability of the head to write on high coercivity (but otherwise thermally stable) media.

In bit patterned media, each magnetic bit is physically patterned onto the disk as depicted in Figure 1. Bit patterned media offers a possible route to thermally stable media at densities beyond 1 Tbit/in². However, patterning templates with resolution of 27nm full pitch and smaller and with size and placement tolerances $\sigma < 5\%$ call for alternative lithographic methods since these dimensions are beyond current optical lithography resolution and beyond current e-beam limitations such as resist resolution, writing time, feature placement, proximity effects and stitching errors.

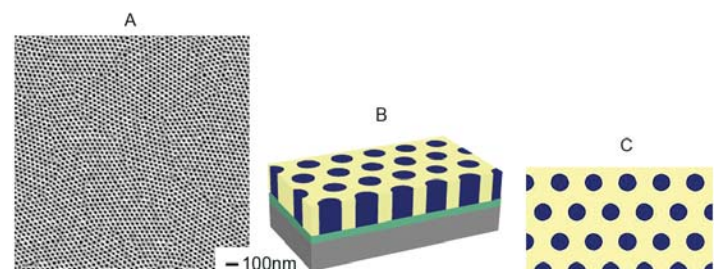


Figure 2: Cylindrical phase block copolymer thin films. A) SEM micrograph of a Polystyrene-*b*-methyl methacrylate (PS-*b*-PMMA) block copolymer. B) Cartoon representation of the block copolymer film with PMMA cylinders in blue and a PS matrix in yellow. C) top-down view of B).

The Method

Block copolymer self assembly provides a route to achieve sub-lithographic resolution at dimensions compatible with the needs of patterned media applications. Figure 2 shows an example of a block copolymer films that form uniform hexagonal array of cylinders with a center-to-center distance, L_0 , that can range between 20 to 50nm depending on the polymer used. This pattern can be used as a lithographic template after selectively removing the material in the cylinder core. However, controlling the ordering, placement and size uniformity has remained

one of the biggest challenges in self assembly for lithographic applications.

Together with our collaborators at the University of Wisconsin, we developed a directed assembly method that combines e-beam lithography with block copolymer self assembly to enhance both resolution and pattern quality when compared to e-beam alone. We use e-beam lithography to generate chemical contrast patterns at specific locations commensurate to the natural lattice of the block copolymer. In this fashion, the e-beam does not necessarily need to write every feature. E-beam can be used to write every other dot (or every other n-dots) and then use the chemical contrast generated on the substrate to direct the assembly of the polymer which registers with the pre-patterned features and multiplies the number of dots. Block copolymers have a unique tendency to maintain a uniform center-to-center distance and a uniform dot size which helps in correcting for any noise or non-uniformities arising from the e-beam pre-pattern. The benefits of directed assembly are twofold: it multiplies the feature density and rectifies the pattern quality.

The fabrication of a master template by e-beam lithography alone is notably challenging. Patterned media specifications place serious challenges on e-beam lithography in terms of placement accuracy, size uniformity and writing time (under ultra-high resolution e-beam lithographic conditions, the time to expose a 95mm disk template could take over a month). The density multiplication and pattern rectification achieved by directed assembly represent an alternative to achieving dense patterns with tight size and placement tolerances, low defect densities and reduced e-beam writing times (see Figure 3).

Block Copolymer Templates

The improved quality of patterning afforded by directing the assembly of block copolymer films on lithographically-defined chemically patterned surfaces in comparison to the lithographically-defined patterns themselves is presented in Figure 4. Figure 4A-D shows top-down SEM images of developed e-beam resist patterned at $L_s=39$, 78, 27 and 54nm respectively. Figure 4E-H shows micrographs of the block copolymer films guided by the pre-pattern with the corresponding e-beam features above. The polymer pitch on the guided patterns (L_p) is 39, 39, 27 and 27nm respectively. In Fig. 4I-L, we plot the dot size distributions of both the e-beam and the corresponding block copolymer patterns from at least 15,000 dots. For $L_s=39$ and 27nm, the e-beam pattern (Figure 4A-C) has a lower quality apparent in variations in distance between rows and dot size distribution.

Both of these sources of noise are rectified by the block copolymer (Figure 4E,G).

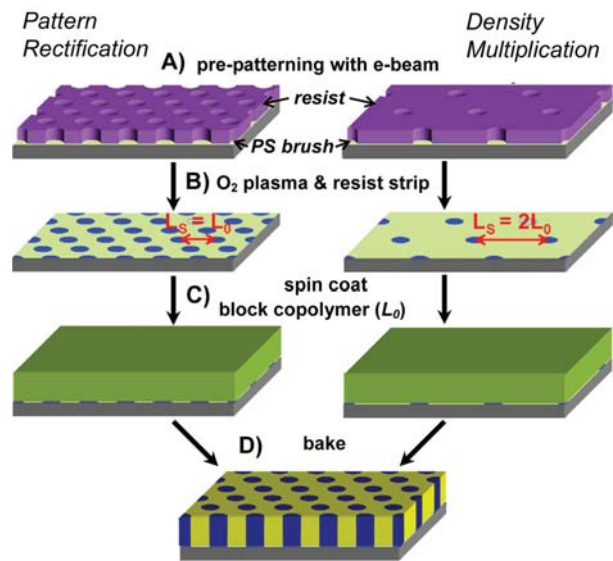


Figure 3: Process to create lithographically-defined chemically pre-patterned surfaces and subsequent directed assembly. (A) Electron beam lithography patterns at $L_s=L_0$ (left) and $L_s=2L_0$ (right). (B) Chemical contrast on the substrate after O_2 plasma exposure on the e-beam defined spots above. (C) Block copolymer thin film. (D) Guided self-assembly in registration with the underlying chemical pattern.

Examples of the density multiplication afforded by the block copolymer are in Figure 4B,F and 4D,H where the e-beam lithography was used to write every other dot and the block copolymer registered with the pre-patterned locations and filled the pattern with extra dots in between effectively multiplying the feature density by a factor of four.

Density multiplication may ultimately pave the way to resolutions not currently achievable by pre-patterning at the limits of e-beam resist resolution and further multiplying to higher densities. With density multiplication, the resolution is increased with respect to the pre-pattern and exposure time is reduced with the decrease in the number of written features (a factor of four in this work, but possibly higher). Additional reductions in writing time follow from the fact that the constraints in defining the dimensions of individual features of the pre-pattern can be relaxed thanks to the rectification action by the block copolymer, enabling the use of faster resists and higher e-beam currents. Thus, writing times for master templates can be reduced from months to days thereby establishing a realistic path towards feature sizes and densities at and beyond the limits of current e-beam tools and resists.

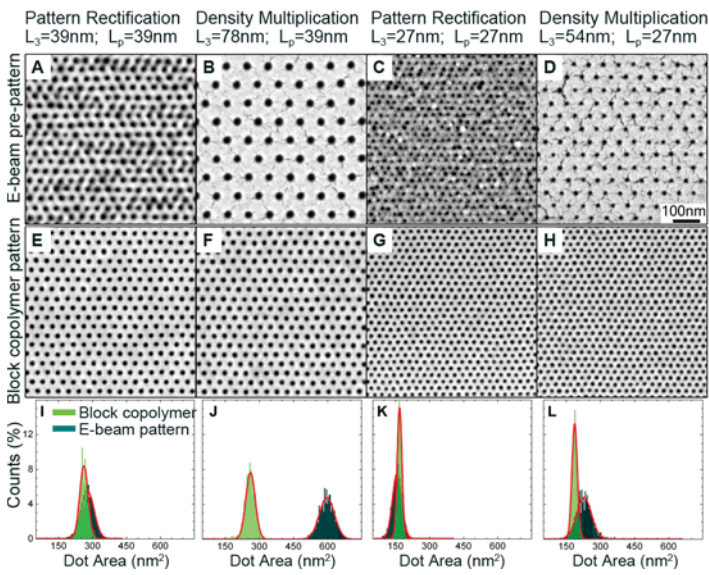


Figure 4: (A-D) SEM micrographs of developed e-beam resist with $L_s = 39, 78, 27$ and 54 nm respectively. (E-H) SEM micrographs of the block copolymer film on top of the pre-pattern defined by the corresponding e-beam pattern above. The lattice pitch on the block copolymer samples is $L_p = 39, 39, 27$ and 27 nm, respectively. (I-L) Dot size distribution of e-beam (dark teal) and guided block copolymer patterns (light green).

Larger area images that show the high degree of uniformity and placement accuracy achieved by the block copolymer density multiplication are shown in Figure 5 for patterns at 490Gb/in² (Figure 5A) and 1Tb/in² (Figure 5B).

Pattern Transfer

A final test for the applicability of the directed block copolymer films relies on its performance as a lithographic mask to transfer the pattern into a substrate. Figure 6 shows the liftoff steps to generate an array of Si pillars from the block copolymer template.

The feature density multiplication and pattern rectification demonstrated by directed assembly provide a method to enhance the capabilities of e-beam lithography enabling higher resolution with improved pattern quality and a reduction of writing time. This method provides a path towards master templates for patterned media storage densities beyond 1Tb/in².

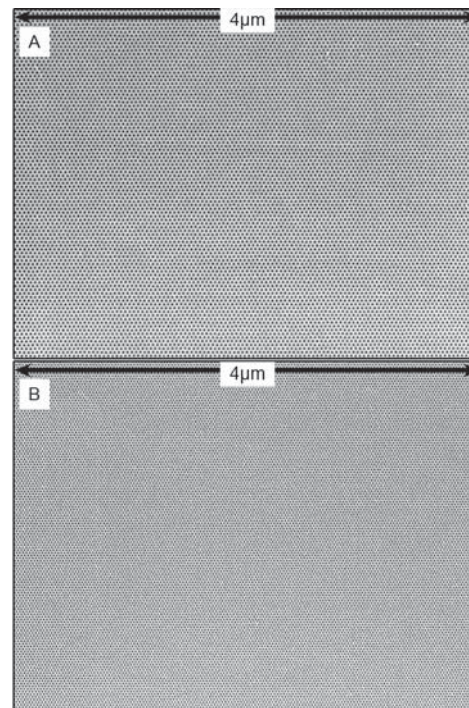


Figure 5: Large area SEM micrographs of density multiplied patterns with (A) $L_s = 78$ nm, $L_p = 39$ nm, and (B) $L_s = 54$ nm, $L_p = 27$ nm.

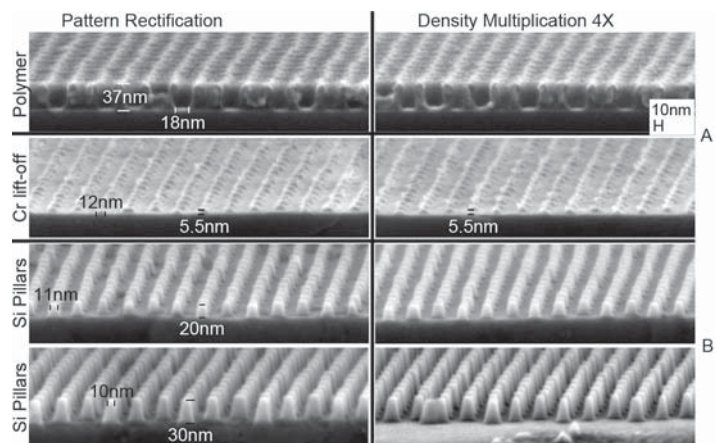


Figure 6: Pattern transfer using a directed block copolymer template with density multiplication ($L_p = 39$ nm, $L_s = 78$ nm). (A) Cr dots after lift-off. (B) 20 and 30 nm tall Si pillars etched using the Cr mask in (A).

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Hitachi Global Storage Technologies
3403 Yerba Buena Road
San Jose, CA 95135 USA

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