Magnetic resonance lithography

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The inverse of magnetic resonance imaging provides a simple approach to super-resolution lithography that can write arbitrary patterns with high contrast.

High-resolution lithography is essential for the miniaturization of electronic processing and storage elements, development of metamaterials, and even biological applications. Optical approaches to nanolithography have long been of interest because they offer the ability to write large-area patterns in parallel. In addition, optical radiation is non-ionizing and thus inflicts less damage than short-wavelength, higher-energy techniques, such as electron-beam or deep-UV lithography. However, for optical lithography to be useful for nanoscale applications, it is necessary to overcome the diffraction limit to resolution. To this end, many super-resolution approaches have been proposed over the last few years, including quantum lithography,\textsuperscript{1} coherent multi-photon lithography,\textsuperscript{2, 3} donut beam techniques,\textsuperscript{4–6} and Rabi flops.\textsuperscript{7} Here we propose a much simpler approach based on magnetic resonance imaging (MRI).

In high-resolution optical lithography the desired pattern is transferred onto a substrate using a variety of techniques, the simplest of which is imaging using lenses. The pattern is then made permanent by the exposure of a photoresist. The photoresist can be used to control subsequent etching and deposition, or can even be part of the final device. In our proposed magnetic resonance lithography approach, the pattern is first transferred to a thin layer of material containing electron or nuclear spins. This is done by applying magnetic gradient fields and microwave pulses that look similar to the signals acquired during a conventional MRI scan (see Figure 1). Since the desired pattern is written in spin sub-levels that do not have enough energy to expose photoresist, an optical readout is required. This is accomplished using materials exhibiting optically detected magnetic resonance (ODMR) of which nitrogen-vacancy (NV) color centers in diamond are a prime room-temperature example.\textsuperscript{8–10}

To write arbitrary 2D patterns with magnetic resonance lithography, multiple lines are written in sequence, in analogy with the multiple lines comprising an MRI image. Figure 1 shows simulation results based on using the three magnetic energy (spin) sub-levels of the NV diamond ground state. The spins are first initialized by some combination of optical pumping and microwave pulses. A line is selected by applying a magnetic gradient field in the x-direction while a microwave pulse is applied near resonance with the 1→2 transition. As seen in Figure 1, the population of spin level 2 acquires the intended line pattern. Next, the x-gradient is replaced by a y-magnetic gradient and

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a complex pulse near resonance with the $2 \rightarrow 3$ transition is applied, which contains the Fourier transform of the portion of the arbitrary pattern to be written along the selected line. As seen, the population of level 3 acquires a single line of the intended 2D pattern, without significant background population at non-intended locations.

In summary, we have used simulations to show that it is possible to write a pattern in the spin levels. More research is needed to demonstrate that we can actually write the pattern and transfer it to the photosensitive material. While a number of problems still remain to be solved before the proposed MRI-based super-resolution lithography can become a viable alternative to existing techniques, our work represents a key step. By identifying a simple approach to solving the physics of sub-wavelength lithography, we have freed up future resources to concentrate on the more challenging problem of resist exposure. The next steps consist of identifying a photosensitive material that can work well with the ODMR material, increasing the aerial density of spins while maintaining long coherence times, and developing ODMR materials with better contrast\textsuperscript{11} and/or upconversion fluorescence.\textsuperscript{12}

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