Nanofabrication via Atom Optics with Chromium

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ABSTRACT

Through the use of light forces exerted by near-resonant laser light, chromium atoms are focused as they deposit onto a substrate, forming nanometer-scale structures on the surface. The laser light is in the form of a standing wave, in which each node acts as an atom-optical "lens." The result is a highly accurate array of lines with a periodicity of $\lambda/2$ = 212.78 nm and full-width at half maximum as small as 38 nm. We discuss progress with this process, in particular the fabrication of a two-dimensional array, the creation of an array with $\lambda/8$ periodicity, the replication of the array in polymer material, the production of magnetic nanowires, and the reactive-ion etching of a chromium pattern on silicon to generate an array of distinct nanowires and/or nanotrenches.

Keywords: atom optics, atom lithography, laser-focused atomic deposition; light forces, atom manipulation, nanostructures, nanofabrication, chromium, magnetic nanostructures

1. INTRODUCTION

Since the first suggestions that laser light could be used to focus a thermal beam of atoms,[1] in particular to nanometer-scale spot sizes,[2] there has been increasing interest in investigating the possible application of this phenomenon to nanostructure fabrication. The reason for this interest lies in several factors that suggest atom focusing could provide an efficient way to fabricate structures in the sub-100 nm regime. For example, thermal atoms have a very short De Broglie wavelength, so the diffraction limitations found in optical lithography are not significant when atoms are used. Furthermore, because atoms do not interact except at extremely close separation, the problems of Coulomb repulsion found in charged particle lithography are not a consideration. Other advantages include the resistless nature of the process, and also the highly accurate periodic focusing arrays that can be realized, making fabrication in parallel inherently feasible.

We report here on advances made in utilizing a standing-wave geometry to focus chromium atoms into arrays of nanometer-scale features on a substrate. The standing-wave geometry has been shown to be a relatively simple approach to laser focusing of atoms that can achieve very high resolution and at the same time pattern a large area all at once. Demonstrations of its use have been carried out with sodium,[3] chromium,[4] and aluminum[5] as the focused atom.

The essential geometry of the standing-wave configuration used in the experiments discussed here is shown in Fig. 1. A laser beam is directed across the surface of a substrate and retroreflected to make a standing wave, and a highly-collimated beam of atoms is incident perpendicular to the surface. The laser beam, typically Gaussian in profile, is positioned so that its maximum intensity is at the surface, i.e., it is cut into a half-Gaussian by the substrate. The laser wavelength is chosen to correspond to a strong resonance in the atom: 425.55 nm (vacuum wavelength) for Cr, corresponding to the $^7S \rightarrow {}^7P$ transition. Because of the resonant interaction between the laser light and the atom, a dipole force is exerted along the

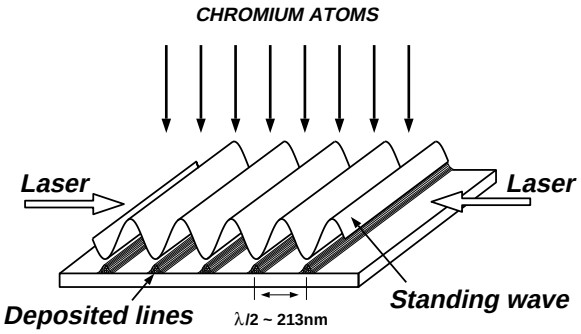

Figure 1. Schematic of laser-focused atomic deposition in a standing wave.

gradient of the light intensity.[6] With a positive detuning, in our case 500 MHz, the force is in the direction of the minima of light intensity, i.e., toward the nodes of the standing wave. Near the nodes, the force is essentially linearly dependent on position because of the nearly quadratic form of the intensity in this region. Thus, first-order focusing is realized and the nodes behave as true atom optical lenses.[7]

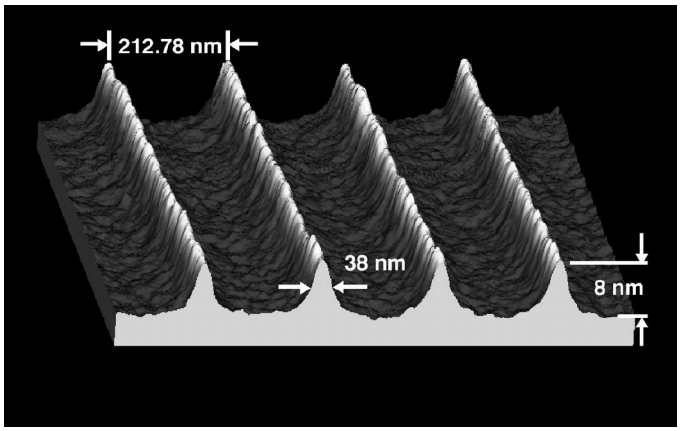

Figure 2. Atomic force microscope image of chromium lines made by laser-focused atomic deposition.

To ensure the smallest possible spots or lines, the atomic beam is collimated to a very high degree before it enters the standing wave. While this could be accomplished with apertures separated by a long distance, there would be in general a large loss of flux associated with this approach. Instead, transverse laser cooling is used to collimate the atom beam. Utilizing the same mirror that retroreflects the standing wave (thereby ensuring alignment), a laser beam detuned below the atomic resonance by one natural linewidth (5 MHz for Cr) is retroreflected with orthogonal polarization ("lin ⊥ lin" configuration) to create a polarization-gradient cooling region. This provides a collimation sufficient for 90% of all atoms in the beam to be contained in an angular spread of 0.6 mrad.[8]

After deposition of a laser-focused Cr pattern on a substrate (typically Si, though GaAs and sapphire have also been used), the sample is removed from vacuum and examined with an atomic force microscope (AFM) in air. Fig. 2 shows what is seen in the region of the sample covered by the laser beam: a regular array of lines with 212.78 nm periodicity and highly uniform height and width. The height of the lines is primarily a function of the atomic beam intensity and the deposition time, and has been varied from 5 nm on some samples to up to 60 nm on others. The width of the lines is a sensitive function of the atomic beam collimation and standing-wave intensity, profile and detuning. By some optimization of these parameters we have reduced the full-width at half maximum from 65 nm in the first demonstrations to 38 nm, as seen in Fig. 2.

2. MORE COMPLEX PATTERNS

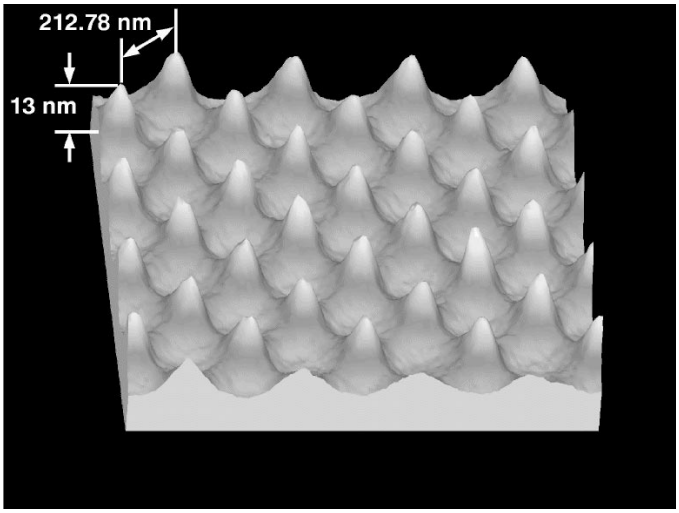

Figure 3. Atomic force microscope image of a two-dimensional array of dots made by laser-focused atomic deposition.

While the parallel fabrication of a highly regular array of nanometer-scale lines on the surface of a substrate has intriguing possibilities for applications such as a nanoscale length standard, an optical grating, or a sensor element, there are also obvious reasons to investigate the capabilities of laser-focused atomic deposition to make more complex patterns. Though creation of a completely arbitrary pattern is still in the future, we have been able to create a two-dimensional array of dots,[9] and also to reduce the line spacing from $\lambda/2$ to $\lambda/8$.[10]

2.1. Two-dimensional array

The two-dimensional array of dots is formed by superimposing two standing waves at 90° across the substrate. While this concept is quite straightforward, there are some subtle effects that must be considered. In general, the two standing waves will have a relative temporal phase that is set by the difference in optical paths taken by the two laser beams. This temporal phase can cause constructive and destructive interference between the two waves, resulting in additional spatial modulation of the light intensity. If the

phase varies, for example as would happen if acoustical vibrations altered the optical path difference, the light intensity pattern would be unstable. To circumvent this potential problem we use orthogonal polarizations in the two standing waves, which results in a cancellation of the interference between them.

An AFM image of a two-dimensional pattern is shown in Fig. 3. The dot spacing is again $\lambda/2$, or 212.78 nm, the peak-to-valley height is 13 nm, and the full-width at half maximum is 80 nm. Current work is concentrated on refining the two-dimensional deposition process, and, should higher-resolution dots be possible, a simple and useful extension would be to translate the sample within the unit cell of the array during deposition. The result would be the parallel fabrication of a large array of arbitrary patterns, a capability that would greatly enhance the versatility of the process.

2.2. Higher periodicity

Fabrication of a higher periodicity array, with lines at a spacing of $\lambda/8$ (or 53 nm), is achieved by taking advantage of a subtle but significant effect in the laser-atom interaction. Instead of using a simple, linearly-polarized standing wave, we rotate the polarization of the retroreflected laser beam by 90° by inserting a quarter-wave plate in front of the retroreflection mirror. This creates a "lin $\perp$ lin" standing wave, which can be conceptualized as consisting of two circularly-polarized standing wave components, one with $\sigma+$, the other with $\sigma-$ polarization, with nodes offset from each other by $\lambda/4$. The laser-atom interaction associated with this light field is described by two arrays of potential wells with periodicity $\lambda/2$, offset by $\lambda/4$. Focusing of atoms occurs not only in all of these wells, creating a $\lambda/4$ periodicity, but also in the crossings of the wells at odd multiples of $\lambda/8$. The crossings focus atoms because they are made into avoided crossings by a coherent coupling induced by Raman transitions between the seven magnetic sublevels of the Cr ground state.

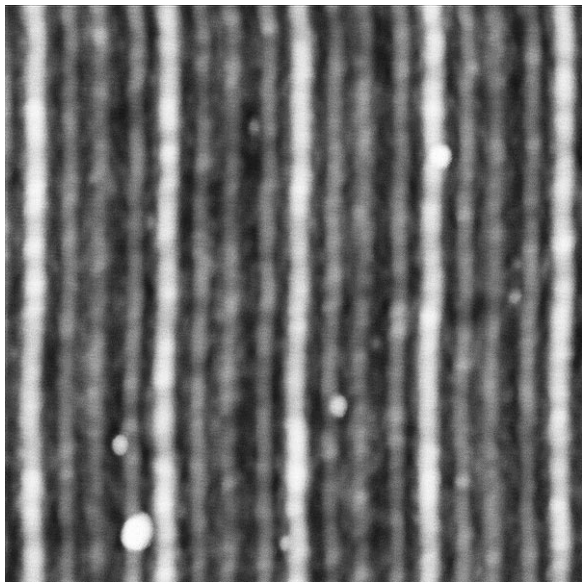

Figure 4. Atomic force microscope image of $\lambda/8$ periodicity in laser-focused chromium. Strong lines are at intervals of $\lambda/2$, and weaker lines are at intervals of $\lambda/8$ (see text).

For a more detailed discussion of the origin of the $\lambda/8$ periodicity the reader is referred to Ref. 10. To illustrate the effect we show in Fig. 4 an AFM image of the pattern, where clear lines at multiples of $\lambda/8$ are seen between the strong lines with $\lambda/2$ periodicity. We note that the relative height of the lines is a sensitive function of the optical state preparation that occurs in the laser cooling region. In fact, quite uniform height has been achieved with proper adjustment of the cooling beams and nulling of the residual magnetic field. Fig. 4 shows a sample created with slightly sub-optimal cooling, so that the additional lines are more clearly distinguishable.

3. OTHER MATERIALS

Chromium is in many ways an excellent material for fabrication of nanostructures. The grain size is typically very small (of order 5 nm or less), the surface mobility is very low, and the stability under exposure to air is excellent due to the tough, thin (about 1 nm) self-passivating oxide that forms. Nevertheless it is important to explore the possibilities for expanding the capabilities of atom optics to include fabrication in other materials. Laser-focusing of other atoms is one approach to this, as has been demonstrated with sodium[3] and aluminum.[5] Another approach is to atom-optically manipulate metastable atoms, and then use these atoms to expose a resist, such as a self-assembled monolayer (SAM) of alkane thiolate.[11] We describe here three further techniques that we have demonstrated recently.

3.1. Replication in a polymer

Polymers constitute a generally inexpensive class of materials that have an extremely wide range of applications. The ability to make polymer structures on the nanometer scale opens a wide range of possible applications that may require mass

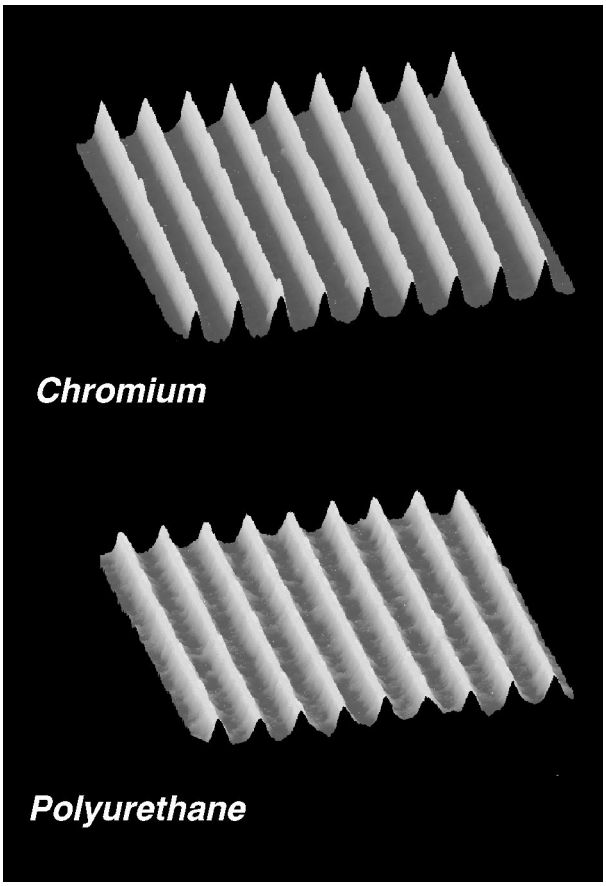

Figure 5. AFM images of chromium lines made by laser-focused atomic deposition and their replica in polyurethane (PU). The Cr lines ar 13 nm high and the PU lines are 8 nm high.

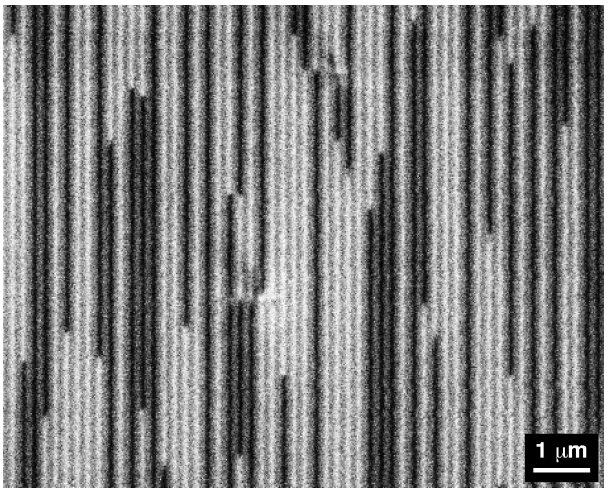

Figure 6. Scanning electron microscopy with polarization analysis (SEMPA) image of magnetic domains in Fe nanowires deposited onto a laser-focused Cr pattern.

production of the pattern or may not be compatible with metal structures. We have shown that it is possible to replicate the Cr pattern made by laser-focused atomic deposition in polyurethane with a very high degree of fidelity.[12] First a complementary mold is made in polydimethylsiloxane (PDMS) by pouring a prepolymer over the Cr master. After curing, the mold is separated and another replication is carried out in polyurethane. The result is shown in Fig. 5, which shows AFM images of the original Cr pattern and its replication in polyurethane.

3.2. Magnetic nanowires

Nanoscale patterning of magnetic materials is of great current interest not only for technological reasons, pertaining to magnetic recording media, but also scientific reasons, stemming from interest in the behavior of magnetic particles with very small dimensions and high aspect ratios. As a demonstration artifact, we have created an array of magnetic wires using a laser-focused array of chromium nanolines. By evaporating iron at a grazing angle of 10°, sufficient shadowing was caused by the Cr peaks to result in an array of distinct Fe wires approximately 40 nm wide, approximately 5 nm high, spaced 212.78 nm apart, and up to 150 μm long.

To observe the magnetic behavior of this array of iron wires, we examined it with scanning electron microscopy with polarization analysis (SEMPA).[13] This technique allows the magnetization of a surface to be examined with the lateral resolution of a scanning electron microscope. Fig. 6 contains an image taken over a 10 μm × 10 μm region, clearly showing the iron lines with domains of magnetization either "up" (white), or "down" (black). The gray regions between the white or black lines correspond to the non-magnetic chromium underlayer, which is exposed between the iron lines. The very large length-to-width ratio of the magnetic wires results in a strong shape anisotropy that forces the magnetization to point only in one of the two directions along the long axis of the wires. Thus we have in essence an array of one-dimensional magnets.

3.3. Reactive-ion etching

Reactive-ion etching is a powerful tool for patterning semiconductor materials such as silicon or GaAs. Highly anisotropic etching can be achieved with an appropriate choice of resist and plasma conditions, creating deep structures with smooth, straight sidewalls. Chromium is known to be an excellent resist material for reactive-ion etching, so a laser-focused atomic deposition sample was etched to investigate its suitability. A possible complication could arise because the chromium patterns that have been produced to date have a background of chromium between the lines. This background, which is typically about one-fourth the height of the peaks, comes from other isotopes in the atom beam (16%) that do not interact with the laser, and a few possible other causes such as the high-velocity tail of the longitudinal atomic velocity distribution, or wings in the angular

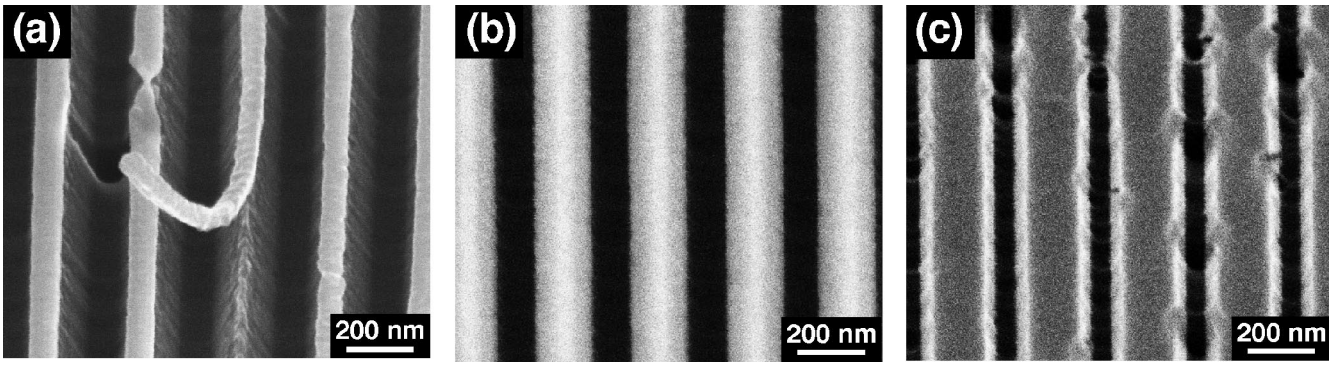

Figure 7. Scanning electron micro-scope images of reactive-ion etched laser-focused Cr on Si. (a) Cr nanowires with approximate width 68 nm; (b) Cr ribbons with approximate width 100 nm; (c) trenches in Si with approximate width 40 nm.

distribution of the transversely-laser-cooled atoms. Its presence could in principle interfere with etching of the substrate in the spaces between the lines. We have found, however, that the background of chromium between the lines is not a serious impediment to etching highly regular patterns into the silicon substrate.[14] Apparently the plasma removes chromium slowly and evenly by a sputtering process until the regions between the lines are exposed. At this point the chemical reactivity of the plasma plays a major role, rapidly removing substrate material to form a trench. It is perhaps surprising that this process, which must be a highly sensitive function of Cr thickness, should yield such highly regular structures. The regularity is due largely to the high degree of smoothness and evenness found in the laser-focused Cr lines.

Fig. 7 shows scanning electron microscope (SEM) images of a sample etched in a RF plasma of SF_6. The image in Fig. 7a shows a region of the sample where the Cr background level was smallest. Here we find that the Cr is reduced to an array of very narrow (nominally 68 nm) wires on top of Si peaks. While some of the wires have broken free, as seen in the figure, there are also large areas where the pattern is intact. Fig. 7b shows another region of the sample where the background level is higher. In this region we find robust Cr "ribbons" nominally 100 nm wide, separated by trenches in the silicon nominally 200 nm deep. Fig. 7c shows what is found in the areas with the highest background, around the edges of the region covered by the laser beam. The sputtering has only just broken through the background here, so the pattern consists of a Cr film cut by a uniform array of narrow trenches approximately 40 nm wide and 90 nm deep.

4. FUTURE PROSPECTS

We have described advances made in the generalization of the laser-focused atomic deposition technique to include some more-complex patterns and also fabrication in other materials besides chromium. These demonstrations show that there is a great deal of potential for this technique, and also that there is much research to be done. Besides pursuing further the avenues outlined above, progress is expected on such topics as atom-optical phenomena, surface growth and diffusion, and materials issues. Atom optics is still a relatively new field and we need to learn more about how atoms interact with more complex light fields, how to manipulate atoms in other ways (such as holography[15]), how to create the brightest, most monochromatic sources of atoms, and what the ultimate resolution limits are for focusing atoms. Surface growth and diffusion are critical to understand; no matter how small a focal spot is obtained atom-optically, the atoms are deposited on a surface and growth and diffusion will ultimately determine the shape and size of the structures fabricated. Materials issues are important to consider because these determine the ultimate applicability of the process to a given technology.

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