Laser-Focused Atomic Deposition – Nanofabrication via Atom Optics

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Abstract

In conventional molecular-beam epitaxy, atoms from a diffuse source randomly impinge upon a surface, accumulating in atomic layers or islands. We have recently demonstrated an enhancement of this process, in which the trajectories of the atoms are controlled with nanometer-scale resolution during deposition. Using the forces exerted by laser light tuned near an atomic transition, an array of "atom lenses" is formed, which focus, or concentrate the atoms into an array of lines or dots with size as small as 30 nm. This new technique represents a novel form of nanofabrication that can create nanometer-scale structures in parallel over a large (millimeter-size) area without the use of any resist or pattern-transfer techniques.

1. Experimental results

Laser-focused atomic deposition has been demonstrated using sodium,[1] chromium[2,3] and aluminum[4] atoms depositing onto a substrate through a laser standing wave grazing across the surface (see Fig. 1). By tuning the laser near an optical absorption line (425.55 nm vacuum wavelength for Cr), a potential energy surface is created that follows the intensity of the laser light. Atoms incident near a node of the standing wave feel a force toward the node and are focused as they deposit.

Using atomic force microscopy to analyze the nanostructures fabricated in this manner, we have observed highly-regular arrays of chromium features with height up to 60 nm and widths as small as 28 nm.[5] Two examples of such structures are shown in Fig. 2. In exploring extensions of the technique, we have created arrays of dots by depositing in a two-dimensional standing wave[6] (Fig. 3), arrays of lines with eighth-wavelength (53.2 nm) periodicity by depositing in a polarization-gradient standing wave[7] (Fig. 4), and patterns in Si by reactive-ion etching the Cr-on-Si system[8] (Fig. 5). We have also duplicated the Cr pattern using polymer molding replication techniques[9] (Fig. 6).

In another approach to utilizing atom optics for nanofabrication, metastable rare-gas atoms have recently been shown to be effective as an exposure tool for lithography. Because the motion of metastable atoms can be controlled with laser light in ways similar to the control of chromium or alkali atoms, all the potential advantages of atom optics (e. g., high resolution, parallel fabrication, and low surface damage) can be put to use in a new lithography process. Resist systems that have been demonstrated for metastable atom lithography include alkane thiolate self-assembled monolayers,[10] "contamination" lithography,[11] and depassivation of hydrogen-passivated silicon.[12]

2. Conclusions

With the demonstrations of the basic principles of laser-focused atomic deposition and the few extensions discussed here, the basic processes of a new technology have been explored. To further develop this technology, future work will involve a higher level of control over growth processes during deposition, improvement of atomic source characteristics, and extension of this process to other material.

References

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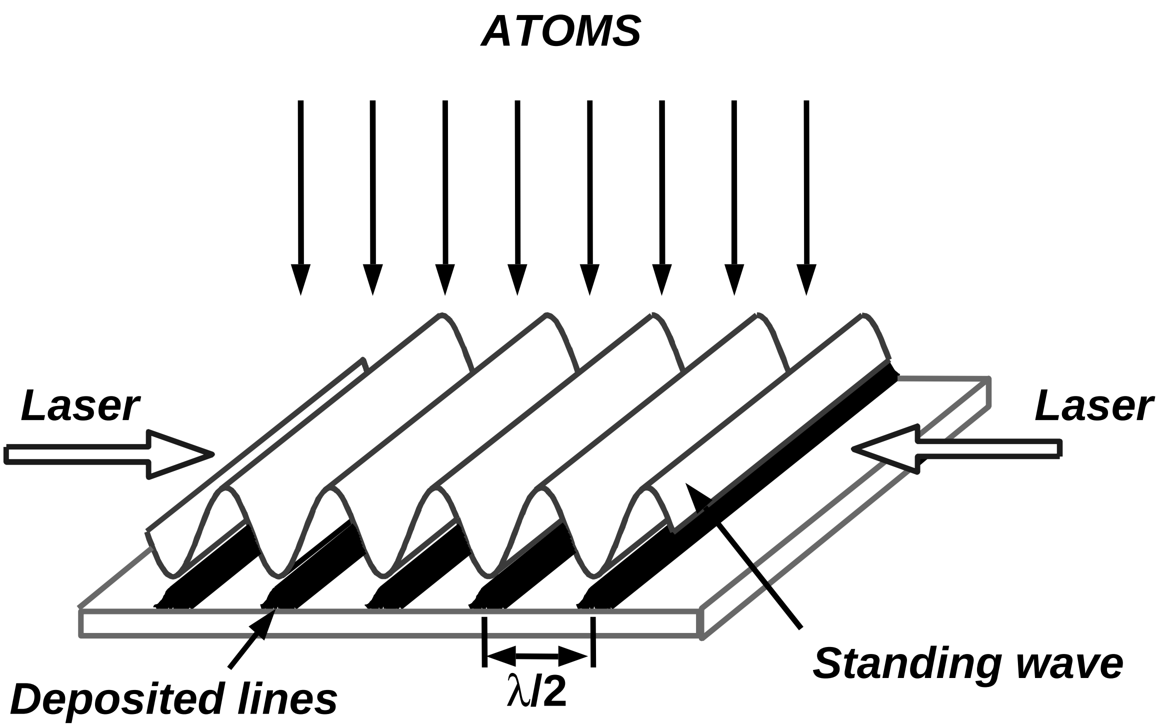

Figure 1. Laser-focused atomic deposition. Atoms pass through a near-resonant laser standing wave as they deposit onto a surface. An induced dipole moment on the atom interacts with the laser light to cause a force toward the nodes of the standing wave. The resulting nanostructures can be as narrow as 28 nm, and are spaced at exactly half the laser wavelength.

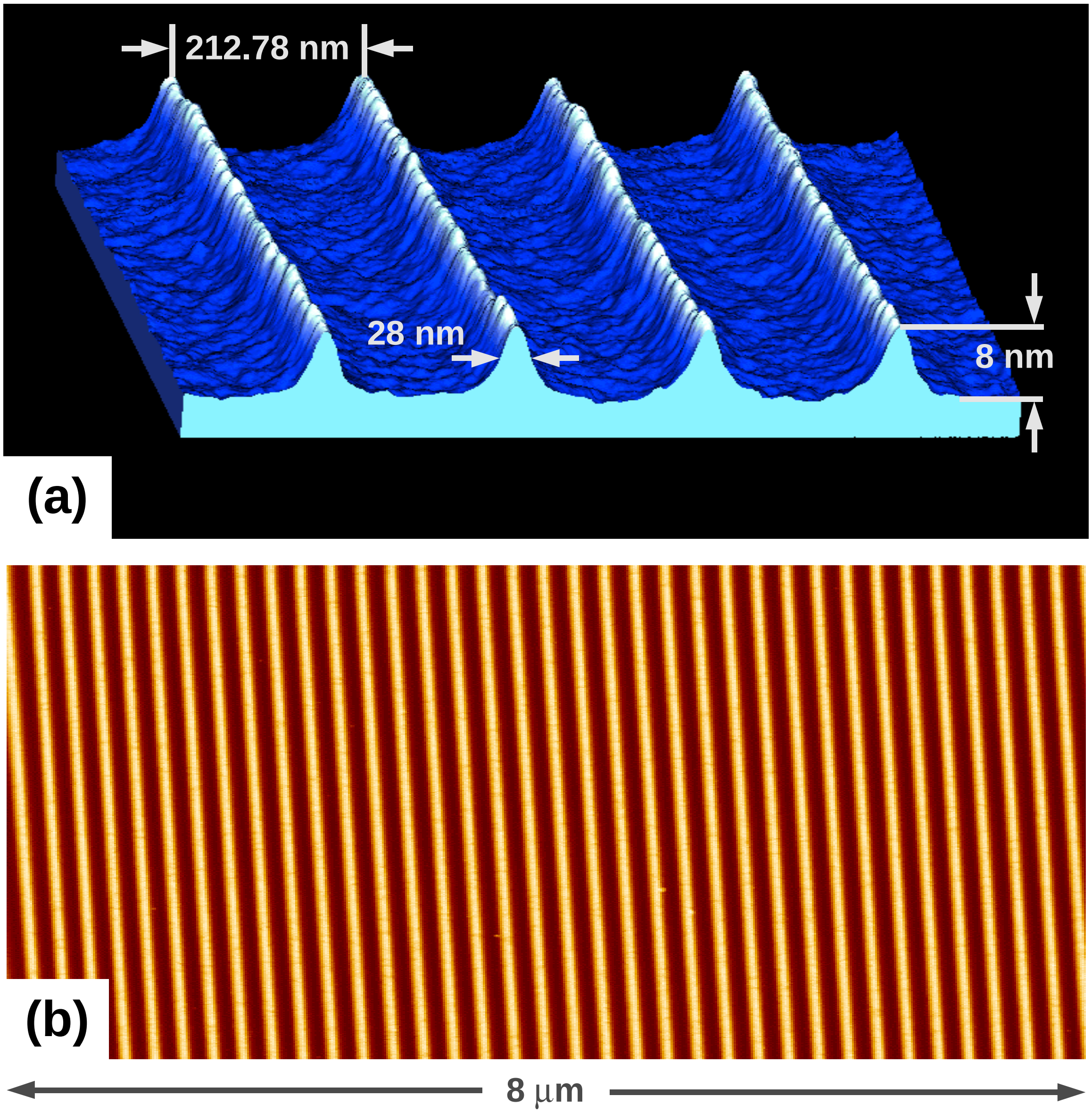

Figure 2. Atomic force microscope images of laser-focused chromium nanostructures. (a) Three-dimensionally rendered view showing some of the narrowest features created in Si; (b) long-range plan view of 60-nm high features on sapphire, illustrating the uniformity attainable in the process.

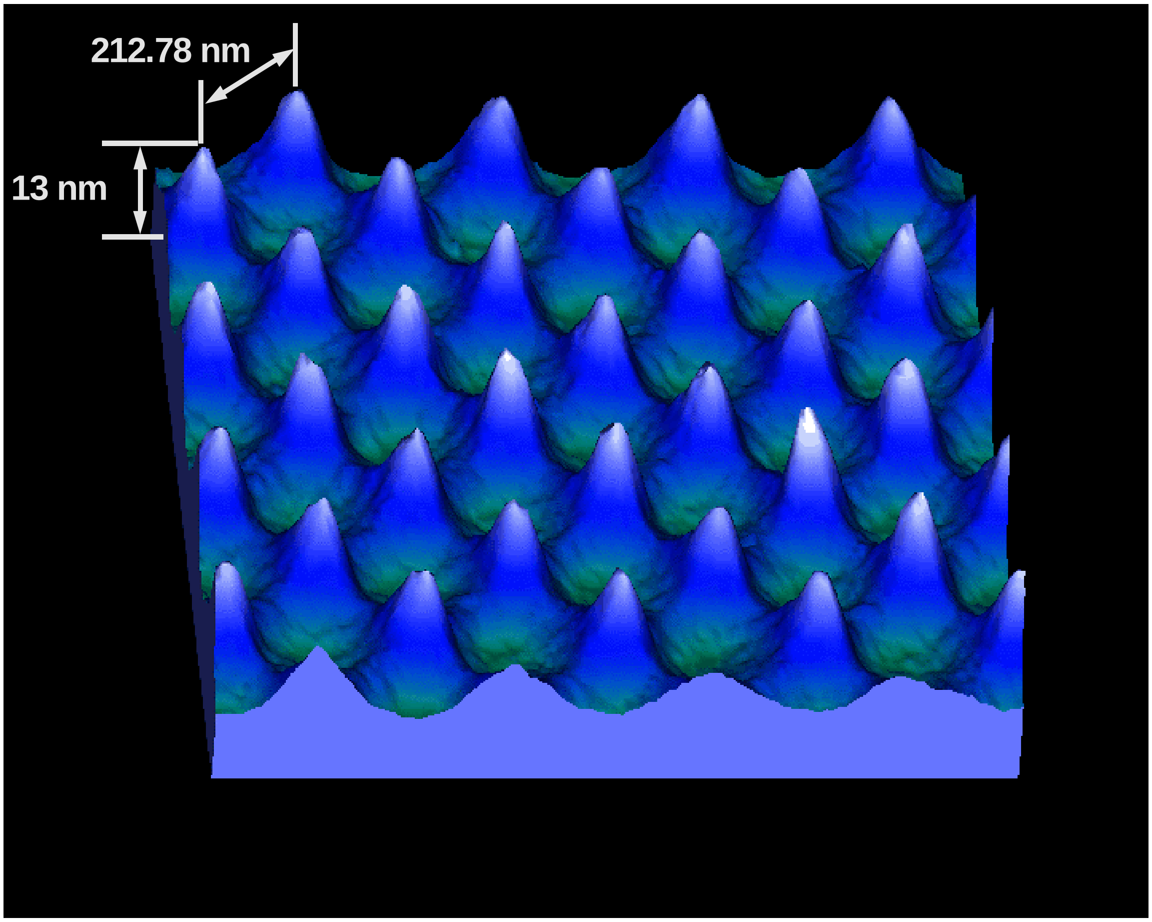

Figure 3. Two-dimensional array of Cr features created by laser-focused atomic deposition.

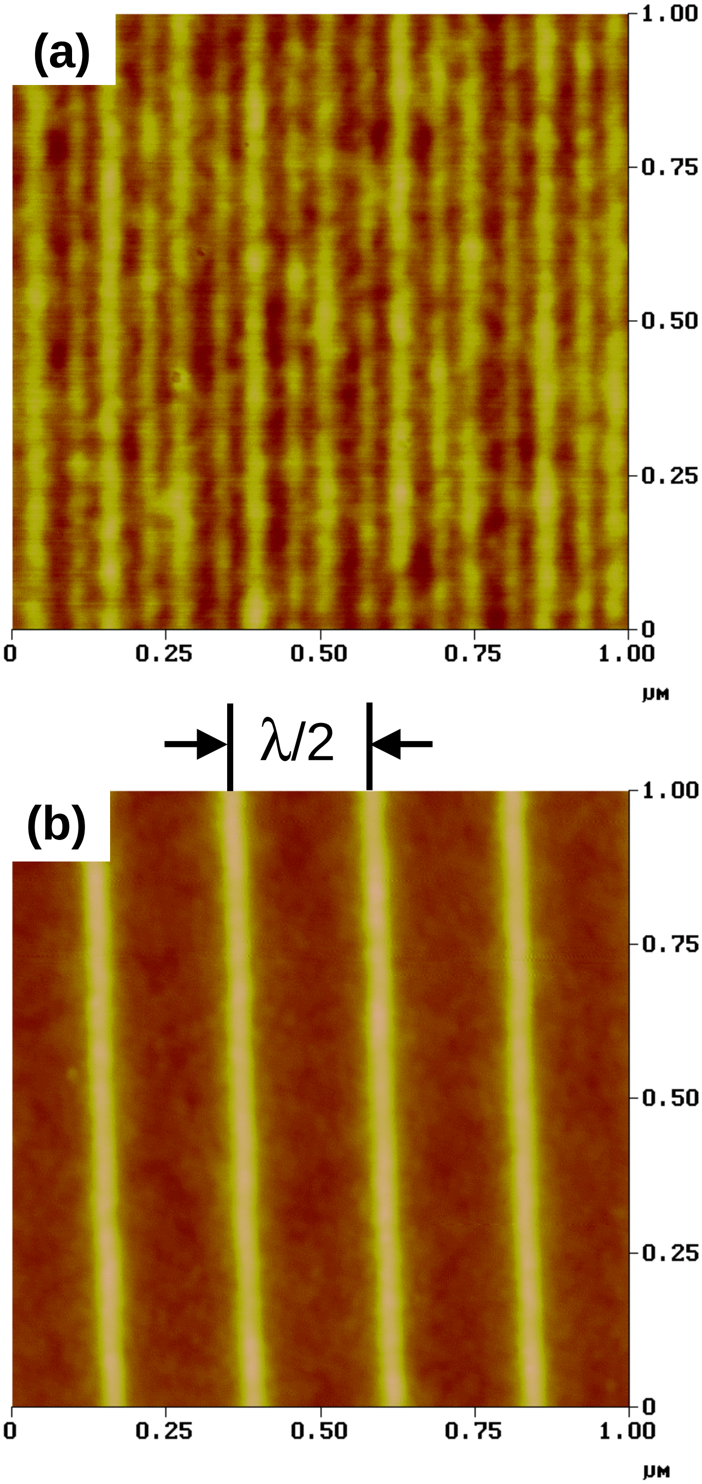

Figure 4. Eighth-wavelength line spacing in laser-focused atomic deposition, achieved by introducing polarization-gradients into the standing wave (a), shown with standard half-wavelength deposition for comparison (b).

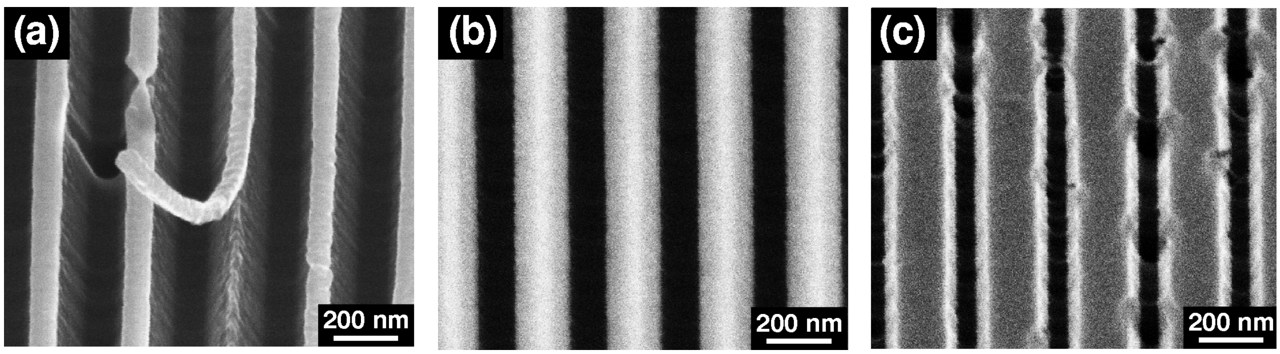

Figure 5. Structures formed by reactive-ion etching of laser-focused Cr nanostructures. (a) 66-nm wide wires formed when Cr contrast is highest; (b) uniform trenches in the Si substrate formed at medium Cr contrast; (c) narrow trenches formed at low Cr contrast.

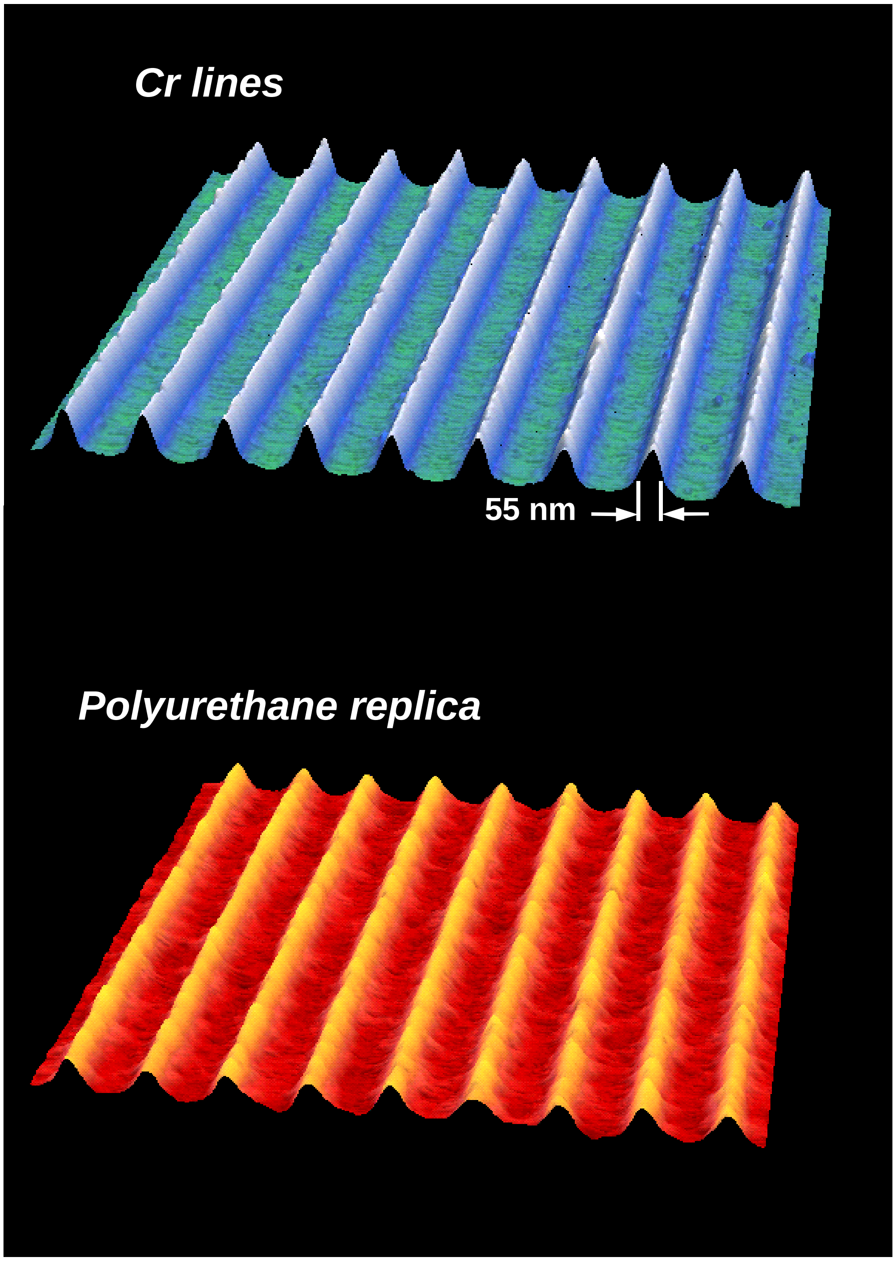

Figure 6. Replication of laser-focused chromium nanostructures using polymer molding techniques.