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FABRICATING NANOSTRUCTURES USING OPTICAL FORCES ON ATOMS

R. Gupta, R. E. Scholten,† J. J. McClelland and R. J. Celotta
Electron Physics Group, National Institute of Standards and Technology
Gaithersburg, MD 20899.

We have demonstrated the use of the optical dipole force in a standing wave to focus chromium atoms into narrow lines as they deposit onto a silicon substrate. An array of chromium lines has been fabricated, with width of 65 nm and spacing of 213 nm.

As electronic and magnetic devices continue to become smaller, the need for fabricating structures on the nanometer scale grows larger. In The lithographic techniques, the fundamental limitation in making nano-scale structures is imposed by diffraction effects. Consequently, technologies are being driven towards using photons of shorter wavelength and/or high energy electrons or ions to produce structures with the highest resolution.

We are currently exploring the techniques of atom optics to fabricate structures on the nanometer scale. Atom optics treats neutral atoms, which can have extremely small de Broglie wavelengths, in an analogous way to light beams or charged particle beams. In atom optics, "optical elements" such as lenses, mirrors and beamsplitters are used to manipulate the atoms' trajectories. Focusing of neutral atoms can be achieved in a number of ways, including passing them through a microfabricated zone plate [1], or subjecting them to the light forces exerted by near-resonant laser light [2]. Optical forces can be either dissipative in nature, in which case they can cool, collimate and/or intensify an atom beam [3], or conservative, in which case they can serve as a lens [4].

In our experiments we use the dissipative spontaneous force to collimate a beam of chromium atoms and the conservative dipole force to focus the atoms as they deposit onto a Si substrate [5]. The dipole force arises from the interaction of the induced dipole in an atom with the gradient in the laser intensity. The intensity variation in the standing wave acts as a series of cylindrical lenses, spaced by $\lambda/2$, which can focus atoms in the nodes (antinodes), when the laser frequency is tuned above (below) the atomic resonance. The first demonstration of laser focused atomic deposition was byTimp *et al.*, using sodium [6].

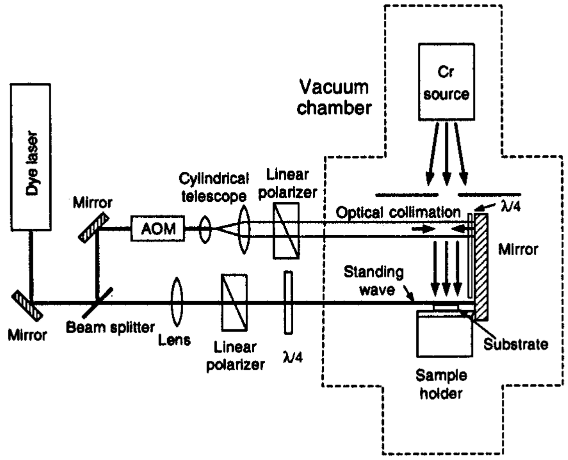

Figure 1 Schematic of laser focused atomic deposition apparatus.

Figure 1 shows a single-frequency dye laser which provides laser light for both the optical collimation and the standing wave. The dye laser is tuned 10 MHz below the atomic resonance to collimate the atom beam and 500 MHz above the atomic resonance for focusing the atoms. The frequency of the dye laser is calibrated against a chromium saturated absorption cell.

Optical collimation of the atom beam is necessary because the final spot size of the focused atoms depends directly on the collimation angle. A pair of counterpropagating laser beams, with orthogonal laser polarizations, is used to transversely cool the atoms. We have made a quantitative study of the temperature of our transverse laser cooling as a function of the laser intensity, detuning and interaction time.

The standing wave laser, with $1/e^2$ diameter 0.4 mm, grazes across the sample so as to generate a half-Gaussian intensity distribution with maximum at the surface of the substrate. Figure 2 shows an atomic force micrograph of a section of the chromium lines created by deposition through the standing wave. The laser wavelength fixes the spacing between the lines at 212.78 nm. Lines extend over the entire region covered by the laser beams. The linewidth is measured to be 65 ± 6 nm and the height of the structures is 34 ± 10 nm.

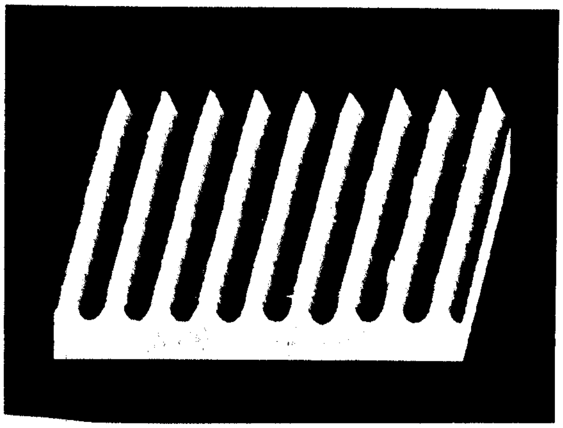

Figure 2. A typical AFM image of the Cr lines.

We have also succeeded in doing preliminary experiments to generate two dimensional patterns through the superposition of two standing waves at right angles. Such a configuration produces either an array of crossed perpendicular lines or spots depending on the laser frequency. In the future, efforts will be made to monochromatize the beam and make other improvements to reduce the linewidth of these structures. With the generation of spots of minimal size the substrate could be translated under the lens to write an arbitrary pattern in a massively parallel manner.

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References

1. O. Carnal, M. Sigel, T. Sleator, H. Takuma, and J. Mlynek, Phys. Rev. Lett. **67**, 3231 (1991).
2. V. I. Balykin and V. S. Letokhov, Physics Today **42**, 23 (April 1989).
3. V. I. Balykin, V. S. Letokhov, and A. I. Sidorov, JETP Lett. **40**, 1026 (1985); B. Sheehy, S.-Q. Shang, R. Watts, S. Hatamian, and H. Metcalf, J. Opt. Soc. Am. B **6**, 2165 (1989).
4. J. J. McClelland and M. R. Scheinfein, J. Opt. Soc. Am. B **8**, 1974 (1991).
5. J. J. McClelland, R. E. Scholten, E. C. Palm and R. J. Celotta, Science **262**, 877 (1993).
6. G. Timp, R. E. Behringer, D. M. Tennant, J. E. Cunningham, M. Prentiss, and K. K. Berggren, Phys. Rev. Lett. **69**, 1636 (1992).

† Present Address: School of Physics, University of Melbourne, Parkville, Vic. 3052, Australia.