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Laser focused atomic deposition

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ABSTRACT

We have demonstrated the use of a standing-wave laser beam to focus chromium atoms as they deposit onto a silicon surface. A permanent array of Cr lines has been fabricated, with line width 65 nm, spacing 213 nm, and height 34 nm. The array covers an area of 0.4 mm × 1 mm, and was deposited in approximately 10 minutes. The lines made in this way constitute a proof-of-principle of an entirely new approach to nanostructure fabrication, with potential for extremely small feature size coupled with massive parallelism.

1. INTRODUCTION

In this paper we provide a summary of work that has been described recently by the authors in two publications.[1,2]

As electronic devices and microcircuits become more and more compact, there has been an increasing need for fabrication methods that can make structures with nanometer dimensions, that is, well below 1 μm. Traditional optical lithography techniques begin to reach their limit at about 0.5 μm, mainly because this size is of the order of the wavelength of the light used, and diffraction effects prevent smaller features. The technology is being pushed by going to shorter and shorter wavelengths, but gains in feature size appear so far to have been incremental for a number of reasons. To reach the ultimate goal of nanometer-size features, it is becoming apparent that an entirely new technology is required.

2. ATOM OPTICS

One technology that shows promise for circumventing some of the technical difficulties associated with optical lithography is the new field of atom optics. In atom optics, a beam of neutral atoms is treated as conceptually analogous to a light beam or a charged particle beam, and optical elements such as lenses, mirrors and beamsplitters are envisioned. Because of their mass, neutral atoms can have very small de Broglie wavelengths (of order 0.01 nm), so the diffraction limit is substantially reduced. Since they are charge-neutral, there are no space-charge effects such as often plague electron or ion optical systems. Atom optics thus has the potential to enable fabrication of much smaller nanostructures than conventional methods, provided focusing techniques can be developed.

Focusing of neutral atoms can be achieved by a number of means, including passing them through a microfabricated zone plate,[3] or subjecting them to the light forces exerted by near-resonant laser light.[4] Light forces can be either dissipative in nature, in which case they can be used to cool, collimate and/or intensify an atom beam,[5] or conservative, in which case they can serve as a lens.[6]

The dissipative character of light forces, most pronounced when the laser is tuned very close to an atomic resonance, is a result of spontaneous emission. The force results from absorption of directed momentum from the laser and isotropic re-radiation of momentum through spontaneous emission. Atomic populations can be cooled (or collimated) using this force by tuning counterpropagating laser beams just below the atomic resonance. Atoms with higher velocity are Doppler shifted closer to resonance with one or the other of the laser beams and hence absorb more momentum. As the atoms absorb momentum, their velocity decreases, and they interact less with the laser. The result is a velocity-dependent force that dissipates energy in the system.

Light forces can also be conservative, and this character is most pronounced when the laser is tuned relatively far from resonance, where there is little spontaneous emission. In this regime the force can be thought of in a classical model involving the induced electric dipole in the atom. The laser field, an oscillating electromagnetic field, induces an oscillating electric dipole

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moment that oscillates either in phase or 180° out of phase with the field, depending on whether the laser is tuned below or above resonance. If the laser electric field has a gradient the induced dipole moment of the atom feels a force in that gradient, either toward higher intensity if the laser is below resonance or toward lower intensity if the laser is above resonance. Given typical atomic parameters and moderate laser intensities available in the laboratory, the depth of the potential created by the dipole force can be of the order of 1 μeV, which, while small, is sufficiently large to generate significant focusing.

To demonstrate the use of atom optics for nanostructure fabrication, we have made use of the dipole force present in an optical standing wave to focus chromium atoms as they deposit onto a silicon substrate (Figure 1). The first demonstration of laser focused atomic deposition in a standing wave was by Timp *et al.*, using sodium.[7] However, the fabricated structures were not stable in air, and could only be observed by optical diffraction. A standing wave provides an excellent intensity configuration for utilizing the dipole force because it consists of a regular array of strong gradients. The intensity varies from maximum to zero and back to maximum over the space of half a wavelength, or 212.78 nm in our case. Near the nodes of the standing wave, the light intensity varies quadratically with distance from the node. This variation is exactly what is needed to form a true lens for the atoms, because the deflecting force is proportional to the distance away from the node. The result is that atoms can in principle be focused to extremely small spot sizes.

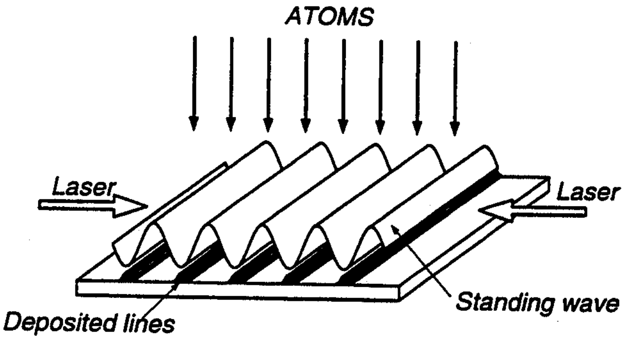

Figure 1. Chromium atoms pass through a laser standing wave as they deposit onto a surface. The nodes of the standing wave focus the atoms into an array of lines on the surface.

3. EXPERIMENT

Our experiment consists of an effusive source of chromium atoms, a pre-collimating aperture, a region of optical collimation in which dissipative light forces are used to transversely cool the atom beam, and a substrate mounted facing the atom beam with

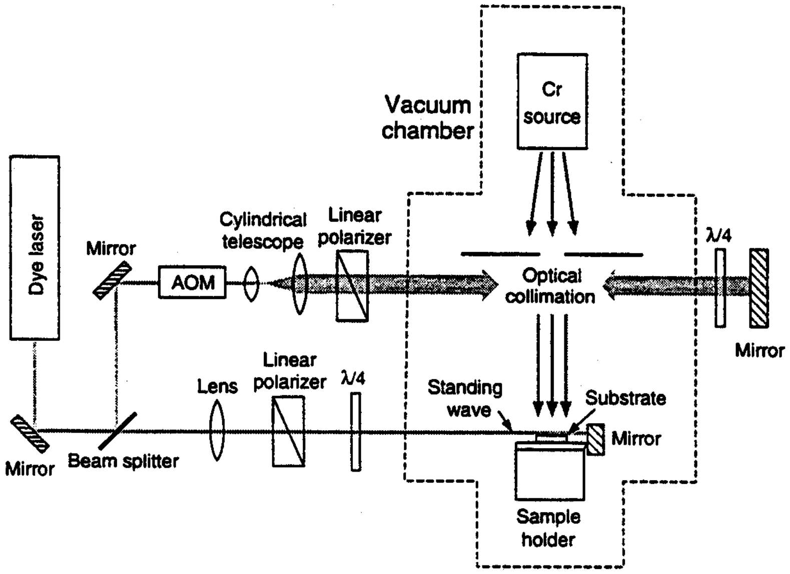

Figure 2. Experimental arrangement for laser focused atomic deposition.

a standing wave grazing across its surface (see Figure 2). The atomic beam source is a commercial MBE evaporation cell, modified to have a 1 mm effusion aperture, operating at about 1575°C. A single-frequency, stabilized dye laser, operating at 425.43 nm with stilbene 420 laser dye and pumped by a UV argon ion laser provides the laser light for both the optical collimation region and the standing wave. The dye laser is tuned 200 MHz above the atomic resonance to generate a standing wave with a strong dipole force. The atomic resonance utilized in the experiment is the ${}^7S_3 \rightarrow {}^7P_4$ transition in chromium. The portion of the laser beam used for optical collimation is frequency-shifted in an acousto-optic modulator to about 2.5 MHz below the atomic resonance.

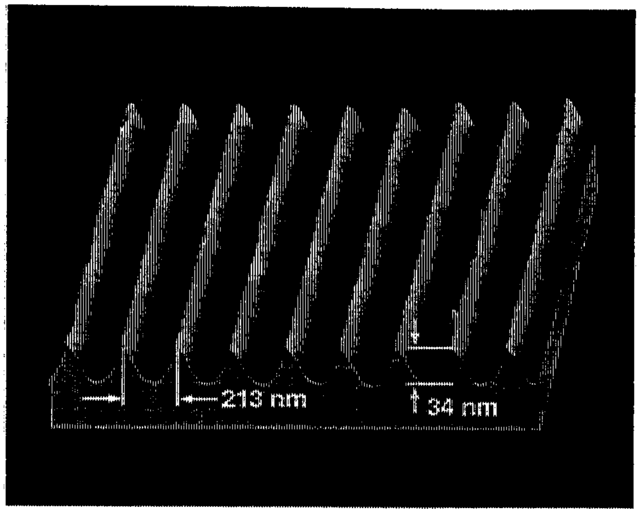

Figure 3. Atomic force micrograph of chromium lines created by laser focused atomic deposition, showing a 2μm × 2μm area. The line width is 65±6 nm, the spacing is 212.78 nm, and the height is 34±10 nm.

The optical collimation of the atomic beam is necessary because of the relative weakness of the potential generated by the standing wave. If the atoms have too much velocity parallel to the substrate surface, they will simply skip across the potential wells rather than being focused. To keep the transverse velocity low enough so that the atoms do not cross between wells, the collimation angle must be less than 1 mrad because the mean longitudinal velocity of the atoms leaving the effusion cell is almost 1000 m/s. This degree of collimation is readily accomplished by using polarization gradient cooling.[8]

The standing wave laser, with mean $1/e^2$ diameter 0.43±0.02 mm, grazes across the sample in such a way as to generate a half-Gaussian intensity distribution with maximum at the surface of the substrate. A low-expansion glass-ceramic plate holds both the sample and a small mirror which reflects the laser beam back on itself, forming the standing wave. In this way, motion of the sample relative to the standing wave nodes (which are fixed relative to the mirror) is kept to a minimum during deposition.

Figure 3 shows an atomic force micrograph of a section of the chromium lines created by deposition through the standing wave. The lines are extremely regular and are visible over essentially the entire area covered by the standing wave laser beam. The line width is measured to be 65±6 nm, and the line height is measured to be 34±10 nm. The spacing of the lines is 212.78 nm, a value which is fixed by the laser wavelength. The atomic force microscope measurements were done in air, after the sample was removed from the vacuum system with no special treatment.

4. CONCLUSION

We have shown that air-stable structures with nanometer dimensions can be fabricated out of chromium using laser focusing of atoms in a standing wave. The lines that have been created by this process possess a number of unique properties which suggest a number of uses. For example, the accuracy of the pitch of the lines appears to be determined solely by the wavelength of the light and any small misalignment that might exist between the standing wave mirror normal and the incident laser. Since the laser light is provided by a single-frequency laser locked to an atomic resonance, the wavelength is known with extremely high precision. The mirror misalignment represents a small perturbation because the pitch only changes with the cosine of this angle, which is quadratic near 0°. Thus the lines have the potential to provide an extremely accurate length standard on the submicron scale.

Since the lines are formed from metallic chromium they should be conductive, suggesting possibilities for examining the behavior of large arrays of nanoscopic conductors. In addition, while chromium itself is antiferromagnetic, the oxide CrO_2 is ferromagnetic, suggesting the possibility of fabricating large arrays of nanoscopic magnetic materials. A further application would make use of the extremely good resistance of chromium to reactive ion etching. This opens the possibility of using the chromium lines as an etch mask, allowing the deposited pattern to be transferred to the sample.

The real utility of this process will be demonstrated when the extension to arbitrary patterns is achieved. One relatively simple approach is to focus the atoms with a two dimensional standing wave, which will result in the deposition of an array of dots, rather than lines. During the deposition, the substrate can be scanned within the range of half the laser wavelength, "painting" an arbitrary pattern within each unit cell. The pattern will be reproduced identically over the entire substrate at a spacing of precisely half the laser wavelength. Thus large arrays of arbitrary structures could be fabricated in a short time because of the parallel nature of the deposition.

5. ACKNOWLEDGEMENTS

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