ROBERT R. McCORMICK SCHOOL OF ENGINEERING AND APPLIED SCIENCE

Nanomaterials

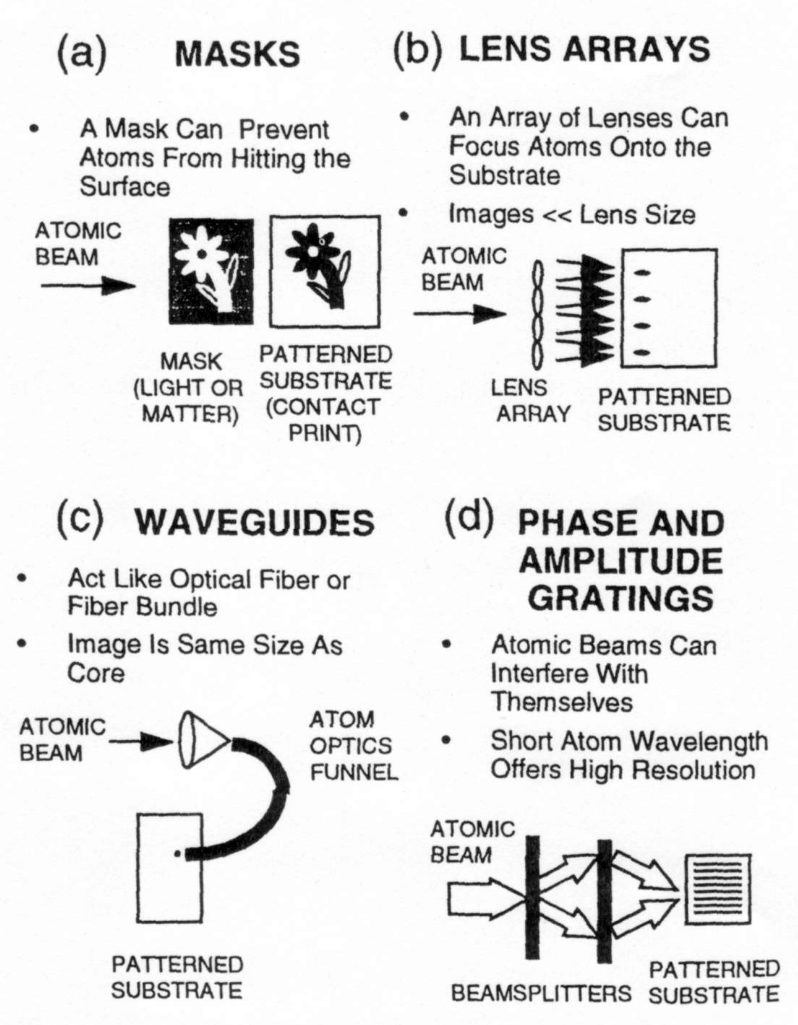
Lecture 4: Atom Optics

Department of Materials Science and Engineering, Northwestern University

Atom Optics

<u>Goal</u>: Develop a maskless, massively parallel, direct-write lithography using light to steer atoms

G. Timp, *Nanotechnology*, Chapter 10



(a) **MASKS**

- A Mask Can Prevent Atoms From Hitting the Surface

(b) **LENS ARRAYS**

- An Array of Lenses Can Focus Atoms Onto the Substrate
- Images << Lens Size

(c) **WAVEGUIDES**

- Act Like Optical Fiber or Fiber Bundle
- Image Is Same Size As Core

(d) **PHASE AND AMPLITUDE GRATINGS**

- Atomic Beams Can Interfere With Themselves
- Short Atom Wavelength Offers High Resolution

FIGURE 1. Atom optics as a tool for nano-fabrication.

Conceptual Approaches for Atom Optics

(1) Mask → Deflect atoms with light or a physical mask (similar to ion beam lithography)

(2) Lens Array → Focus atoms with light

(3) Waveguide → Confine atoms with light

(4) Phase and Amplitude Gratings → Interfere atomic beams (similar to double slit experiment)

Important Experimental Parameters for Atom Optics

Since the ultimate structure on the surface may be different from the intended atom optics due to diffusion/migration of atoms on the surface following deposition, we need precise control of:

(1) Atomic Species

(2) Surface Material

(3) Degree of Surface Contamination

(4) Ambient Temperature

Forces Exerted on Atoms by Light

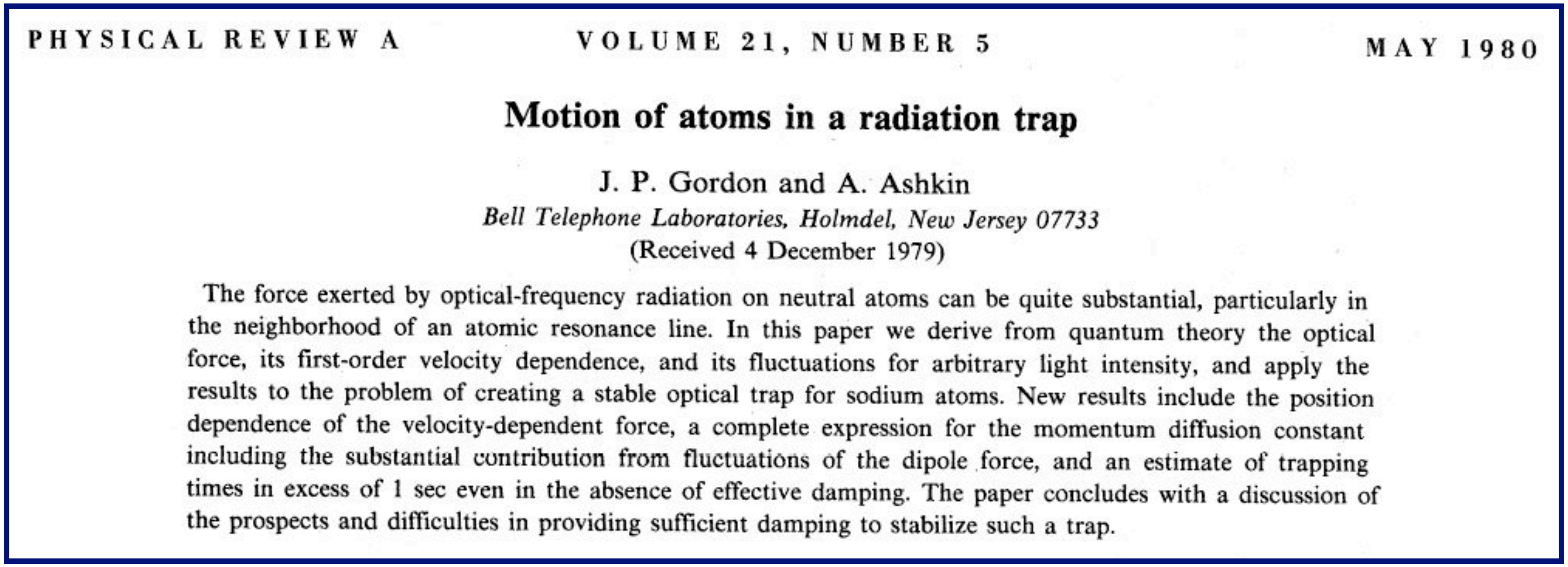
(1) Stimulated or coherent processes
→ energy of the atom is conserved

(2) Spontaneous or incoherent processes
→ energy of the atom is not conserved
→ no analogous behavior in conventional optics

NOTE: Spontaneous processes can "cool" atoms ("optical molasses")

→ Atomic beams can be simultaneously collimated and brightened.

Complete Physical Description



PHYSICAL REVIEW A VOLUME 21, NUMBER 5 MAY 1980

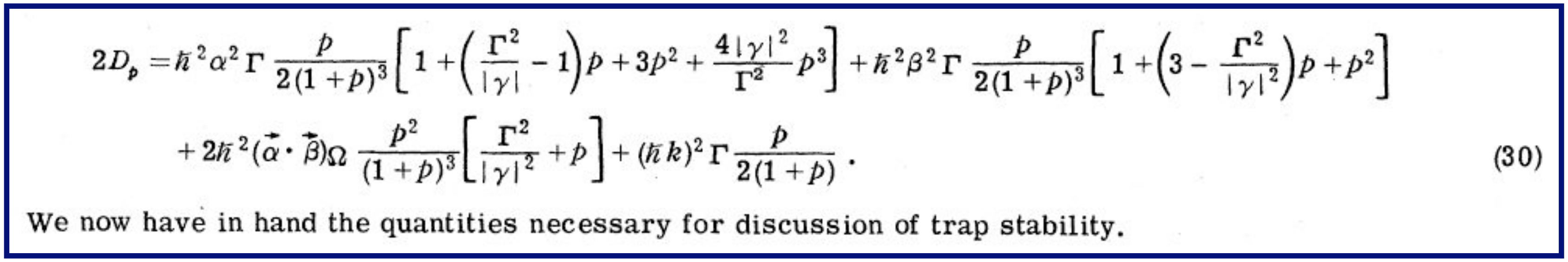
Motion of atoms in a radiation trap

J. P. Gordon and A. Ashkin

Bell Telephone Laboratories, Holmdel, New Jersey 07733

(Received 4 December 1979)

The force exerted by optical-frequency radiation on neutral atoms can be quite substantial, particularly in the neighborhood of an atomic resonance line. In this paper we derive from quantum theory the optical force, its first-order velocity dependence, and its fluctuations for arbitrary light intensity, and apply the results to the problem of creating a stable optical trap for sodium atoms. New results include the position dependence of the velocity-dependent force, a complete expression for the momentum diffusion constant including the substantial contribution from fluctuations of the dipole force, and an estimate of trapping times in excess of 1 sec even in the absence of effective damping. The paper concludes with a discussion of the prospects and difficulties in providing sufficient damping to stabilize such a trap.



$$2D_p = \hbar^2\alpha^2\Gamma\frac{p}{2(1+p)^3}\left[1+\left(\frac{\Gamma^2}{|\gamma|}-1\right)p+3p^2+\frac{4|\gamma|^2}{\Gamma^2}p^3\right]+\hbar^2\beta^2\Gamma\frac{p}{2(1+p)^3}\left[1+\left(3-\frac{\Gamma^2}{|\gamma|^2}\right)p+p^2\right]$$

$$+2\hbar^2(\vec{\alpha}\cdot\vec{\beta})\Omega\frac{p^2}{(1+p)^3}\left[\frac{\Gamma^2}{|\gamma|^2}+p\right]+(\hbar k)^2\Gamma\frac{p}{2(1+p)}\,. \tag{30}$$

We now have in hand the quantities necessary for discussion of trap stability.

J. P. Gordon, *et al.*, *Phys. Rev. A*, **21**, 1606 (1980).

Classical Explanation

- Electric field (***E***) associated with light interacts with induced dipole moment in the atom.
- Dipole moment = $\mathbf{p} = \alpha\mathbf{E}$ (α = polarizability constant)
- Instantaneous energy = $-\mathbf{p}\bullet\mathbf{E}$
- Since the frequency of light greatly exceeds external motion, we must average over an optical cycle:

→ Potential energy = $U = -pE\cos\varphi = -\alpha E^2\cos\varphi = -\alpha I\cos\varphi$

where: φ = phase difference between dipole and field
I = laser intensity

Classical Explanation of Stimulated or Coherent Force

- Below resonance conditions:
  → $0° < \varphi < 90°$ → $\cos\varphi > 0$ → $U \sim -\alpha I$
  → atoms are attracted to intensity maxima

- Above resonance conditions:
  → $90° < \varphi < 180°$ → $\cos\varphi < 0$ → $U \sim \alpha I$
  → atoms are attracted to intensity minima

Classical Explanation of Spontaneous or Incoherent Force

- Results from induced dipole moment that is in quadrature (i.e., 90° out of phase) with electric field.
- Force is proportional to the gradient of the phase of the field rather than the intensity gradient.

NOTE: Classical picture is okay conceptually but subtle details are lost without the help of quantum mechanics.

Quantum Mechanical Explanation

Stimulated or Coherent Force

- Results from absorption and subsequent stimulated emission of photons from atoms (compare to lasers)
- This interaction preserves the coherence of the atomic wavepacket

Spontaneous or Incoherent Force

- Results from absorption followed by spontaneous emission.
- Coherence is not preserved → resulting emission occurs in a random direction

Applications

(1) Optical Molasses

- Two weak counter-propagating traveling wave field detuned below resonance results in cooling
- Used for minimizing transverse kinetic energy in atomic beams
- Leads to collimation of atomic beam

(2) Single Thick Lens

- Co-propagate atomic beam with light detuned below resonance with Gaussian spatial intensity distribution
- Stimulated force focuses atoms to a spot on the substrate

Applications

(3) Mirrors

- Detune above resonance → Potential barrier can reflect atoms
- Atoms only reach substrate where there is no light (masking)

(4) Lens Arrays

- Use a standing wave laser field for periodic focusing
- Lenses are exactly separated by $\lambda/2$
- Add cooling to confine atoms to bottom of potential wells → linewidths can be as small as $\lambda/20$

Schematic of Atom Optics Lens Array

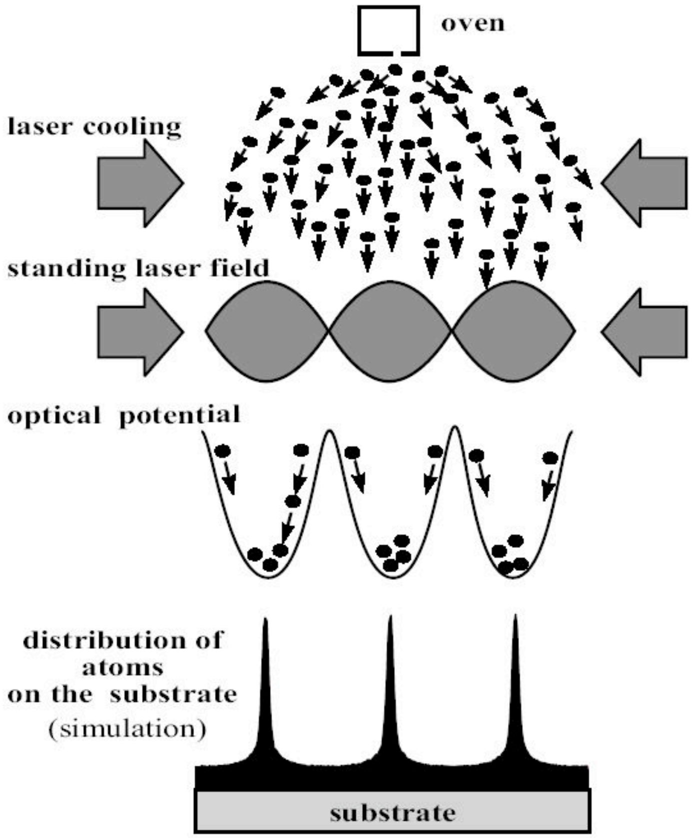


Fig. 1. Basic principle of atom lithography with light forces. The atomic beam is collimated by laser cooling techniques and then focused in a standing laser wave onto a substrate with the periodic structure determined by the nodal pattern

U. Drodofsky, *et al.*, *Appl. Phys. B*, **65**, 755 (1997).

First Experimental Demonstration

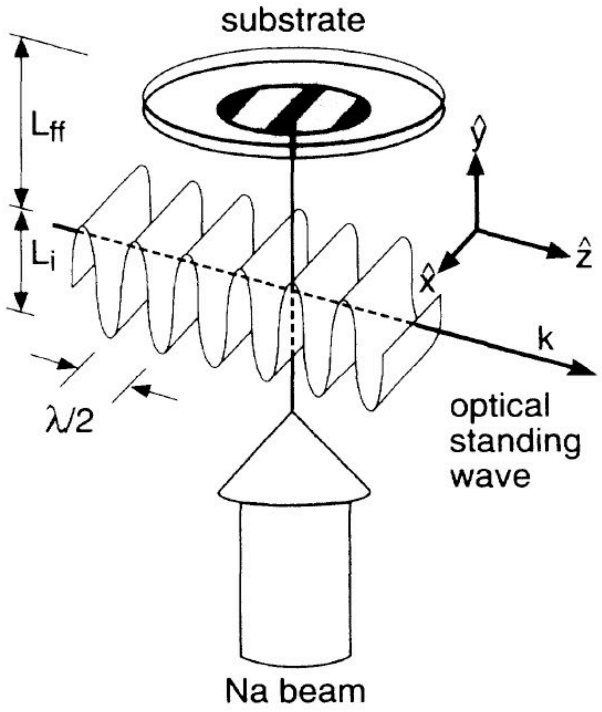


FIG. 1. A schematic representation of the experiment. An optical standing wave is interposed between an atomic beam and a substrate to deflect atoms during deposition.

G. Timp, *et al.*, *Phys. Rev. Lett.*, **69**, 1636 (1992).

Sodium Lines on Silicon

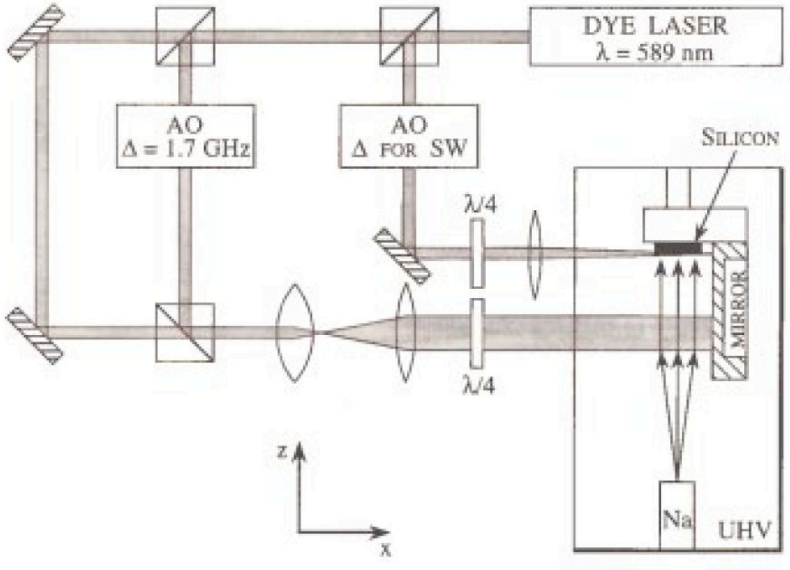


FIG. 1. Schematic of the experiment.

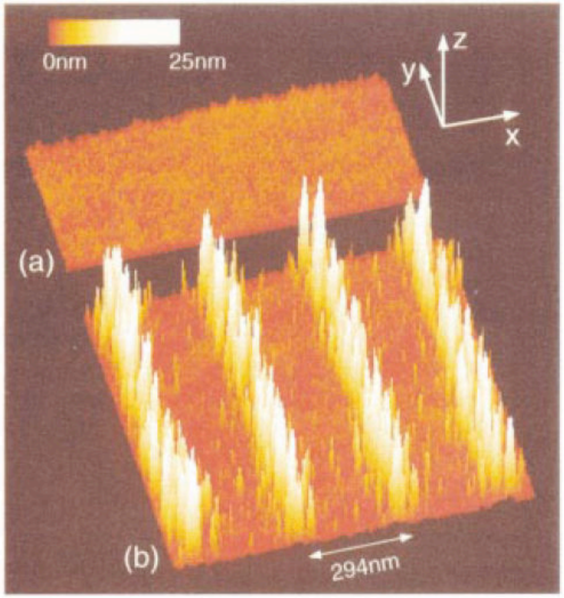


FIG. 2. STM micrograph of sodium grating deposited on silicon. The sodium distribution shown in (b) was obtained under optimal focusing conditions in the SW of $\Delta = +1712$ MHz, $w_0 = 56$ μm, and input traveling wave power of 12 mW. The transverse molasses cooling was adjusted to reach the theoretical Doppler limit of 240 μK. The resultant linewidth is about 45 nm and the contrast is better than 10:1. For comparison, in (a) we show a section of the silicon surface before deposition, imaged under identical conditions.

V. Natarajan, *et al.*, *J. Vac. Sci. Technol. B*, **13**, 2823 (1995).

Schematic for Chromium Lines

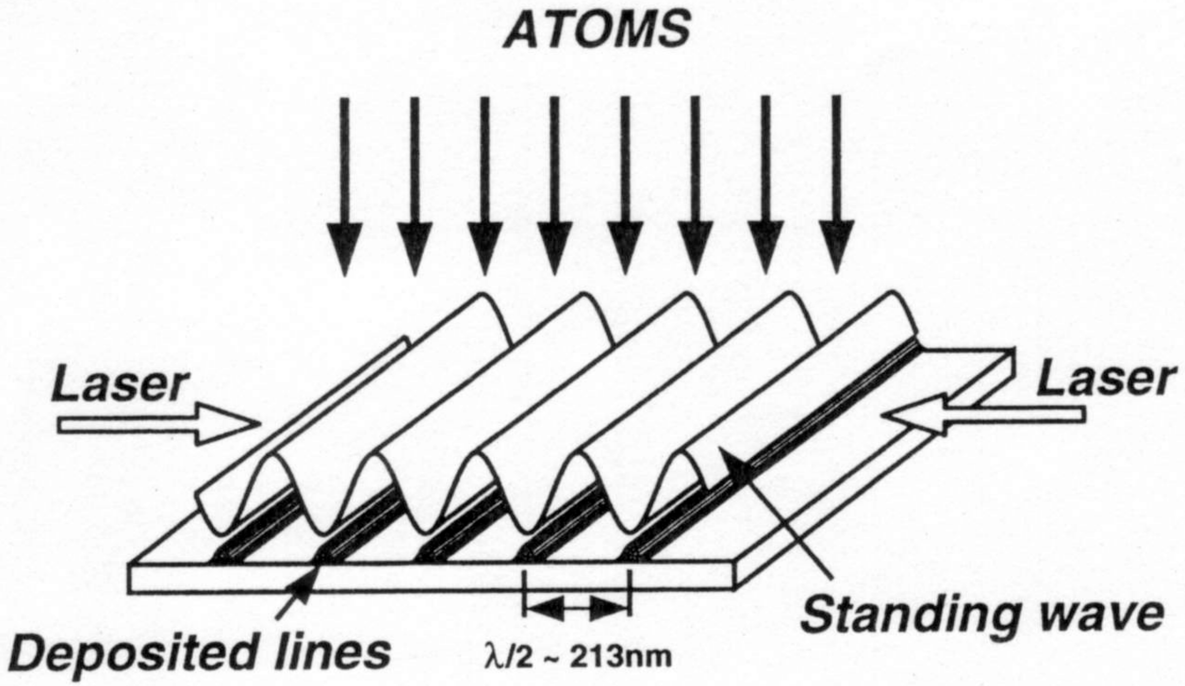


FIGURE 2. Focusing of atoms in a standing wave laser field.

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Chromium Lines on Silicon

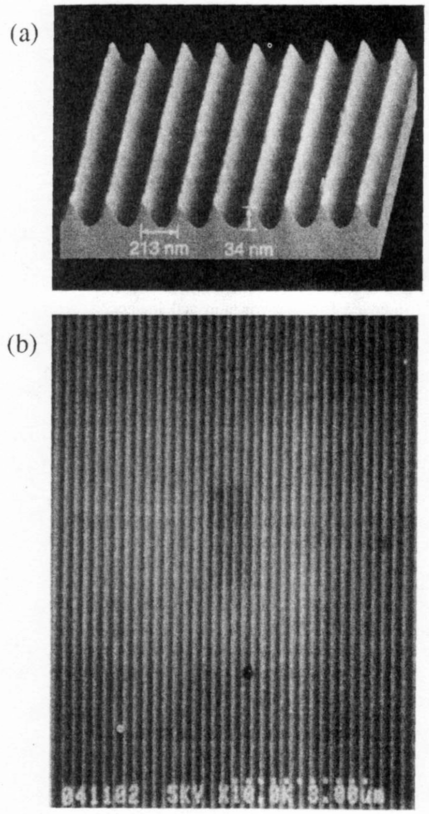

FIGURE 4 (a) Atomic force microscope image of chromium lines created by focusing chromium atoms in a standing wave (ref. [28]). (b) Scanning electron microscope image of chromium lines created by focusing chromium atoms in a standing wave (ref. [29]).

Note the change in period compared to sodium.

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Aluminum Lines on Silicon

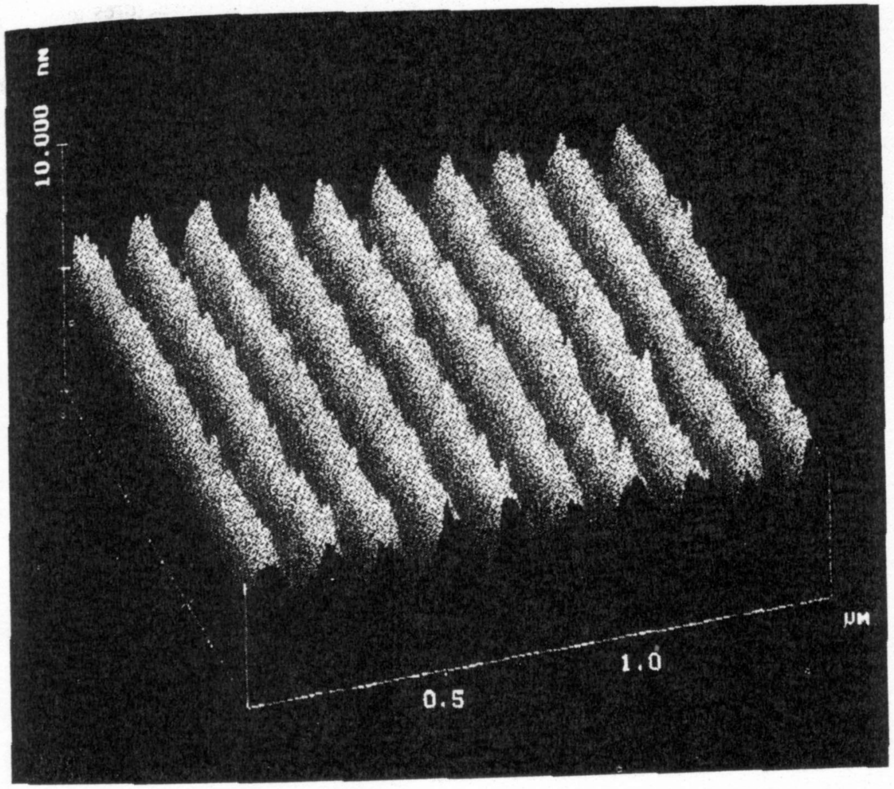

FIGURE 5. Atomic force microscope image of aluminum lines created by focusing aluminum atoms in a standing wave (ref. [31]). (*See color plate.*)

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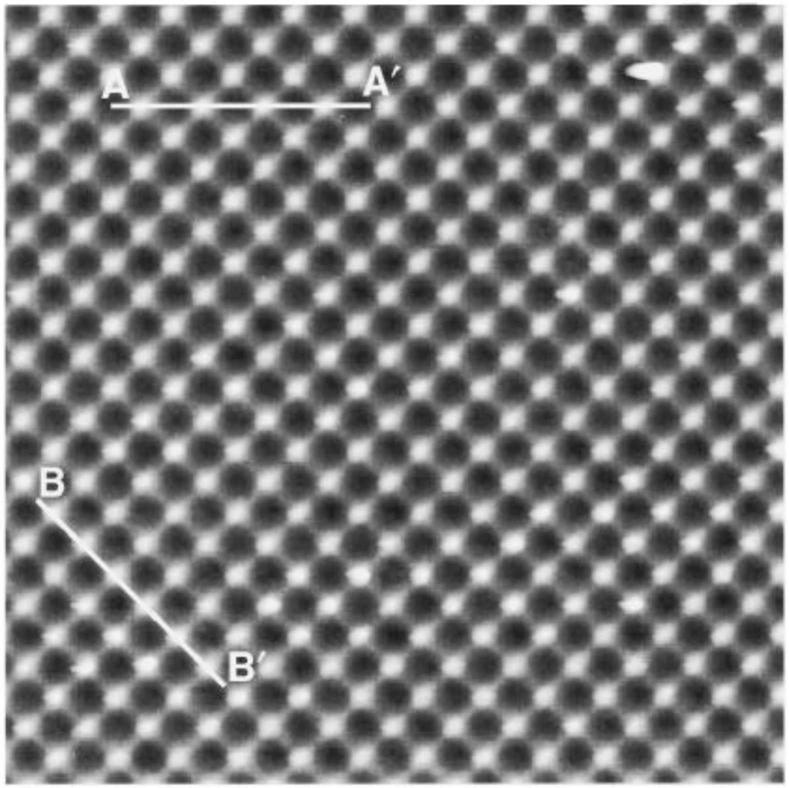
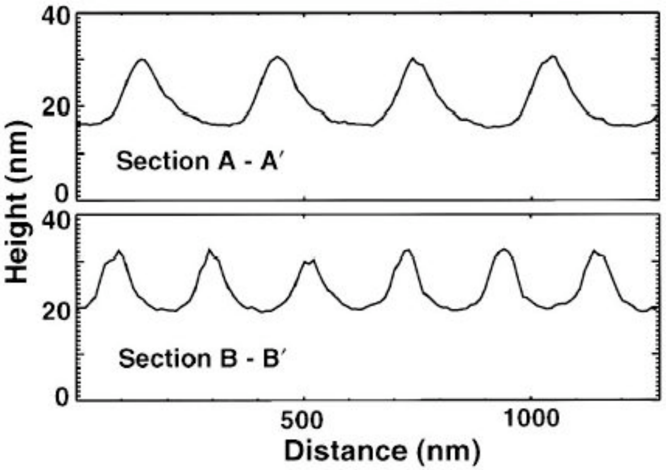
Chromium Square Lattice



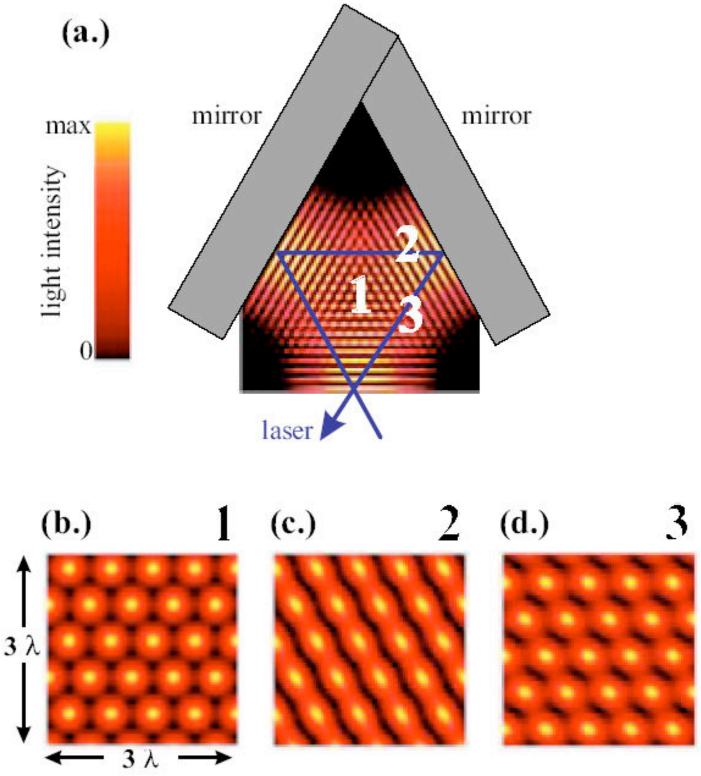


Square array generated by a 2-D standing wave pattern

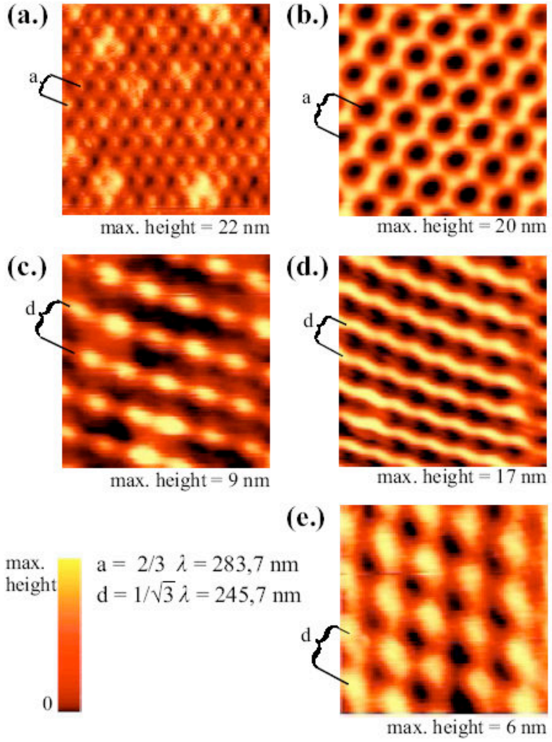
R. Gupta, *et al.*, *Appl. Phys. Lett.*, **67**, 1378 (1995).

Chromium Hexagonal Arrays

Schematic:



Data:



Position #1

Position #2

Position #3

U. Drodofsky, *et al.*, *Appl. Phys. B*, **65**, 755 (1997).

Using Cesium Atom Optics for Alkanethiol Resist Exposure

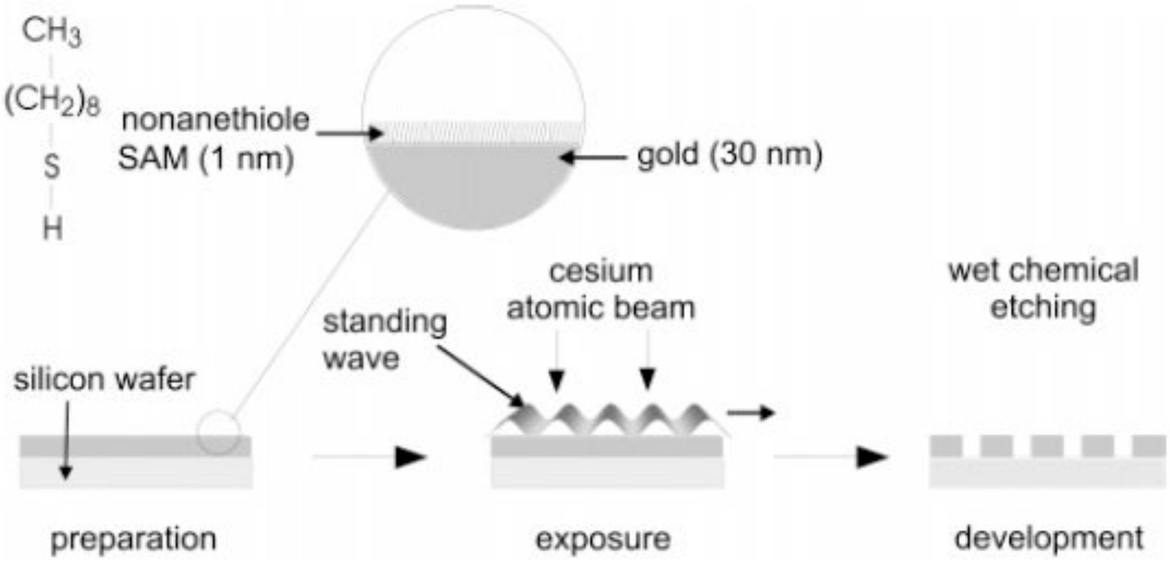


Fig. 3. The lithographic process consists of sample preparation, structuring the resist with a cesium atomic beam, and etching in a gold etching solution

F. Lison, *et al.*, *Appl. Phys. B*, **65**, 419 (1997).

Resulting Patterns of Gold on Silicon

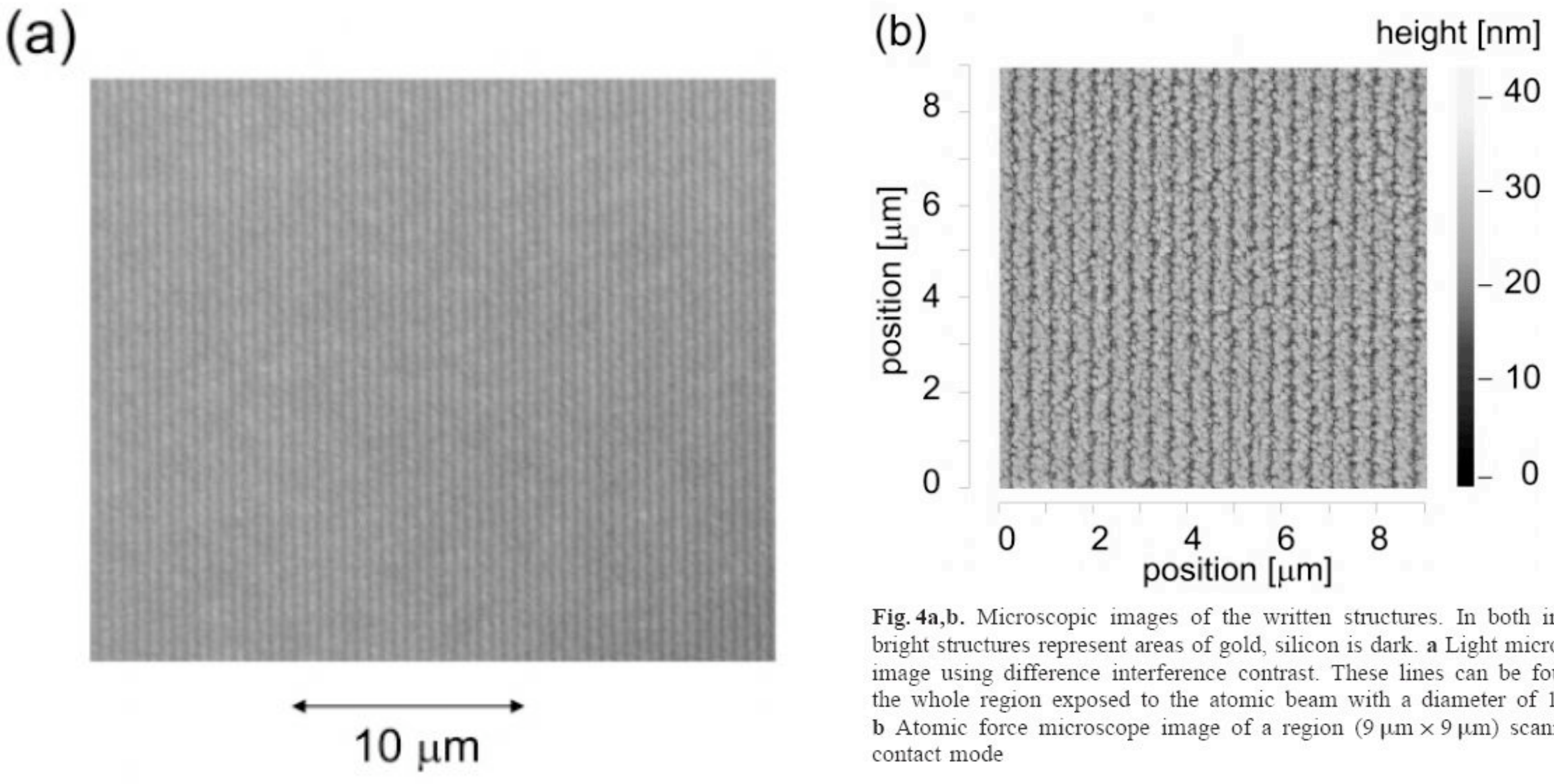


Fig. 4a,b. Microscopic images of the written structures. In both images, bright structures represent areas of gold, silicon is dark. **a** Light microscope image using difference interference contrast. These lines can be found in the whole region exposed to the atomic beam with a diameter of 1 mm. **b** Atomic force microscope image of a region (9 μm × 9 μm) scanned in contact mode

F. Lison, *et al.*, *Appl. Phys. B*, **65**, 419 (1997).

Future Prospects of Atom Optics

Advances are needed in:

(1) Other materials

- Develop lasers that can be tuned to transitions of other atoms
- Use pattern transfer (i.e., expose resists chemically or energetically with atomic beams)

Future Prospects of Atomic Optics

Advances are needed in:

(2) More general patterns

- 2-D standing wave pattern for quantum dots
- More complex standing wave fields are possible
- Scan the beams or substrate for parallel writing
- Combine with masks (only need masks with resolution of ~λ/2 to block atoms)