

## Atom lithography

Atom lithography designates a physical method where the forces exerted by interfering laser beams on the atoms of an atomic beam are used to steer the atoms into nanostructures fabricated on a plane surface. While atom lithography is the most frequently used term, the method is also known as light-force lithography and atomic nanofabrication (ANF).

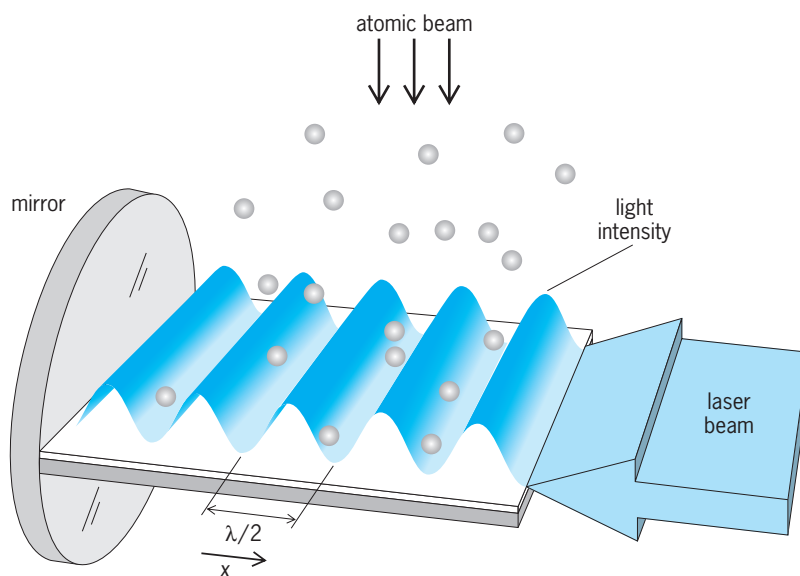
Atom lithography is an application of a field called atom optics. In this field, atomic motion is controlled by means of forces exerted by laser beams or a combination of laser and magnetic forces. All concepts of geometric and wave optics—refraction, diffraction, and interference—are straightforwardly transferred to atomic beams. Wave properties of atomic beams are governed by the de Broglie wavelength,  $\lambda_{\text{dB}} = h/mv$ , where  $h$  is Planck's constant, and  $m$  and  $v$  are the mass and the speed of the atom.

Structure formation by atom lithography relies on the deposition of atoms on a surface. Typical experimental atomic beams have  $1 \text{ mm}^2$  cross section. Taking 1 min as a reasonable exposure time, a beam with flux of the order of  $10^{11}$  atoms per second is required to deposit a single monolayer of atoms.

**Applicability.** Atom lithography is applicable to any element that is able to form an atomic beam and can be manipulated by the methods of laser cooling. It is thus essential that robust and tunable laser light sources are available to excite atomic resonance lines in these atoms. Atom lithography is element-selective since the laser interaction is effective only in the vicinity of atomic resonance lines. Laser cooling is an essential preparation technique for atom optics and thus for atom lithography. It has been demonstrated to work with all alkali atoms, alkaline earths, metastable rare gases, and elements of immediate technological interest, including chromium and aluminum. Further elements such as gallium, indium, iron, and the noble metals are under investigation for this application.

**Standing-wave focusing.** The simplest example of atom lithography is realized using a standing-wave light field which serves as a focusing mask, free from matter, for a suitable substrate (**Fig. 1**). The energy levels of atoms are shifted as they pass through the light field. This light shift is zero at the nodes but elsewhere it is finite, so its spatial nonuniformity corresponds to a spatially varying potential whose gradient results in a force. For the case shown in **Fig. 1**, this force is along the direction of propagation of the laser beam that sets up the standing wave. These forces are called optical dipole forces since they rely on the interaction of the induced atomic dipole moment and the inhomogeneous light field.

The standing wave of the laser radiation acts on the incident atoms as an array of microscopic lenses with apertures  $\lambda/2$ , with  $\lambda$  denoting the wavelength of the laser light field. The lenses focus appropriately directed atoms of an incident beam toward the optical nodes or antinodes, depending on the sign of the difference between the atomic and laser frequencies.



**Fig. 1.** A standing wave acting as an array of microlenses for an atomic beam. The atomic beam is focused into lines. The standing wave is formed by reflection from the mirror of a laser beam of wavelength  $\lambda$ , and the light intensity is proportional to  $\sin^2(kx)$ , where  $k = 2\pi/\lambda$  is the magnitude of the laser wave vector.

The atomic pattern generated on the surface closely resembles the pattern of the intensity distribution of the light mask. The interaction of atoms impinging onto the surface must be local in order to preserve the desired pattern; that is, atoms must not diffuse after deposition.

The standing-wave microlenses are not perfect. Like their conventional optical counterparts, they suffer from multiple aberrations. Spherical aberrations cause a more or less homogeneous background. Beam spread in the transverse direction (failure of collimation) causes broadening of the microlens focus, which can be controlled by laser cooling. Longitudinal velocity spread corresponds to chromatic aberrations and broadens the microlens focus as well; it is, however, tolerable even for thermal atomic beams.

**Methods.** Two basic variants of atom lithography can be distinguished: In direct deposition, the atoms deposited cause a physical modification of the surface. In neutral atom lithography, atoms cause a chemical modification of a resist which is subsequently transferred to the substrate.

*Direct deposition.* The direct deposition method allows layers of atoms to be deposited in a two-dimensional pattern onto a substrate. While the first experiments were carried out with chemically unstable sodium atoms, it was a breakthrough when J. J. McClelland and coworkers demonstrated that atom lithography with chromium atoms could be used to produce a very large array of narrow and strictly parallel lines (**Fig. 2**). Line patterns are typically separated by  $\lambda/2$ , with linewidths of the order of tens of nanometers. Two-dimensional patterns with four- and sixfold symmetry have been manufactured. The direct deposition method offers unique promise for the manufacture of three-dimensional structures at nanometer scales through a growth process.

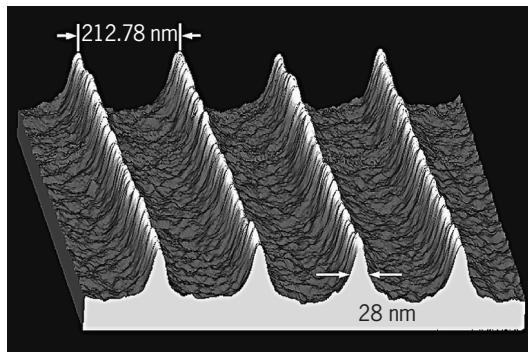


Fig. 2. Direct deposition of an array of chromium lines. (With permission of J. J. McClelland)

*Neutral atom lithography.* In conventional lithography, a material called resist covering a substrate is first chemically modified, for example, in optical lithography, by ultraviolet light. The structures are then prepared through a series of wet chemical processing steps. In neutral atom lithography, the surface modification is caused by reactive atoms (alkalis or metastable rare gases) chemically interacting with special resists such as alkane thioles. After wet etching, the pattern of the light mask used to steer atoms into the surface is precisely reproduced (Fig. 3). In comparison with optical lithography, the roles of light and matter are exchanged: Light serves as the mask determining the pattern to be formed; exposure to the atomic “radiation” causes modification of the resist. See EXTREME-ULTRAVIOLET LITHOGRAPHY.

**Role of laser cooling.** Since the forces exerted by light are small, it is absolutely essential to use only extremely well collimated atomic beams for atom lithography. If an atomic beam is collimated by geometric apertures only, atomic flux is dramatically reduced. Application of transverse laser cooling (the use of lasers to reduce the spread in the transverse components of atom velocities) is thus a necessary prerequisite to implement the methods of atom lithography. This cooling improves the brightness, brilliance, and phase-space density of atomic beams, and these improvements result in a strong enhancement (30–80-fold) of the flux density at the substrate. Transverse laser cooling is compatible with the use of any thermal atomic beam.

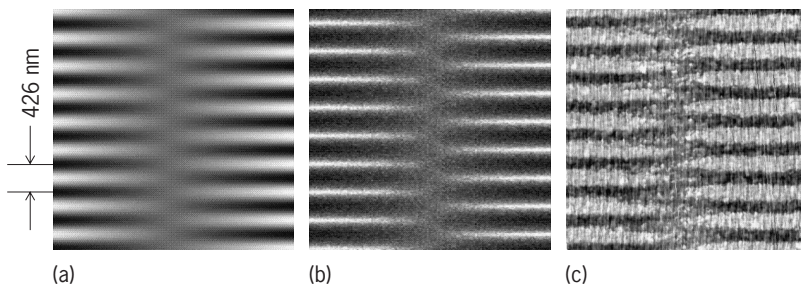


Fig. 3. Manufacture of a nanoscale pattern, with small ( $\lambda/2 = 426$  nanometers) and larger structures, by neutral atom lithography, using a cesium atomic beam and an alkane thiole resist. (a) Intensity distribution of the light mask. (b) Numerically simulated atomic pattern. (c) Actual structure, etched into a 30-nm gold layer.

Longitudinal laser cooling further improves the imaging properties of atom lithography methods by reducing chromatic aberrations. However, not only does its application require costly implementation of multiple laser wavelengths, but it is also in general accompanied by significant flux reduction. Thermal atomic beams (in which the longitudinal velocity spread has not been reduced) thus seem to prove themselves as the sources of choice for atom lithography.

**Technologically relevant elements.** The alkali elements can be controlled with one or two simple infrared diode laser light sources, and atomic beams are easy to operate. Technologically more relevant materials typically require blue or ultraviolet laser light sources. Owing to their complicated hyperfine structure, sometimes several closely spaced laser wavelengths may have to be generated by costly instruments. Nevertheless, implementation of the methods of laser cooling and atom lithography seems realistic for the technologically relevant elements aluminum, gallium, indium, iron, chromium, copper, silver, and gold, and in some cases it is already being carried out.

**Complex patterns.** While large arrays of parallel lines (one-dimensional, or 1D, structures) can be straightforwardly manufactured, it remains to be seen what degree of complexity can be achieved in the atomic pattern deposited. It has been shown that two crossed standing waves result in a square array of dots, and three standing waves can generate hexagonal patterns. Superposition of multiple laser beams (up to 1000 per radian) can be achieved with volume holograms stored in photorefractive crystals.

The first step in the manufacture of a complex atomic pattern is to transfer a two-dimensional intensity pattern of interfering light beams to a substrate. If several elements are synchronously deposited, the variation of the deposition rate as well as the two-dimensional patterning can be used to extend this method to generate materials with three-dimensional modulation of their composition, which is a unique promise of atom lithography.

**Applications.** A natural application of atom lithography is the generation of precision rulers at nanometer scales because the laser wavelength determining line spacing is known with extremely high accuracy. A resolution of 1 in  $10^6$  has been demonstrated. Nanostructures produced through direct deposition of chromium in iron structures also exhibit interesting magnetic properties.

Furthermore, atom lithography promises intriguing opportunities for the generation of three-dimensional structures at nanometer scales which are unique to this method. The direct deposition concept allows growth of a material composed from several elements where the light mask selectively modulates the concentration of one element only. Hence, the periodicity of the light-field intensity distribution will induce a superlattice which could have various applications. For instance, physical properties such as the electronic band structure or the index

of refraction will be subject to periodic modulation at the scale of the wavelength.

**Future challenges.** In a series of beautiful experiments, it has been demonstrated that atomic matter waves can successfully be employed for atomic pattern generation by reconstructing a hologram made by conventional nanolithography. Ultimate wave properties (coherence, focusability) in atom optics are promised by atomic matter waves, or so-called atom lasers. They are derived from atomic Bose-Einstein condensates and can be treated in close analogy to coherent optical beams. However, the maximum flux achieved today is below  $10^6$  atoms per second, and hence their application for atom lithography, which requires deposition of at least  $10^{10}$ - $10^{11}$  atoms per second, seems remote at present. However, a technical breakthrough could rapidly change this situation.

For background information see ATOM LASER; ATOM OPTICS; ARTIFICIALLY LAYERED STRUCTURES;

CRYSTAL GROWTH; HOLOGRAPHY; INTEGRATED CIRCUITS; LASER COOLING; NANOSTRUCTURE; NANOTECHNOLOGY; NONLINEAR OPTICS; OPTICAL RECORDING in the McGraw-Hill Encyclopedia of Science & Technology. Dieter Meschede

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