# Atomic Nanofabrication of Periodic Structures

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**Abstract:** Metastable helium (He*) has 20 eV of internal energy that destroys a molecular resist assembled on a wafer. A standing wave of light $\lambda$=1083 nm was used to channel and focus the He* atoms into lines separated by $\lambda/2$. The lines are transferred to the wafer with a standard etch.



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The ability to record and preserve the positions of atoms in a permanent structure on a sub-micron scale has myriad possible applications. To begin, the structure itself may be of value. Such nano-scale patterns can be made with precise long-range regularity whose spacing is known to spectroscopic precision. Examples include gratings for short wavelength radiation, photonic crystals, metamaterial samples, and many others. Second, the distribution of atoms is determined by light fields so that the pattern produced can be used as a measure of the light intensity distribution. For example, very small deviations caused by wave front imperfections could be detected. Finally, the process by which the light fields influence the atomic motion in forming such patterns is an interesting topic of study by itself.

The first demonstration of atomic nano-fabrication using light fields to steer the atoms was described by Timp et al. with a beam of Na atoms deposited on a glass substrate [1]. Because of the chemical instability of sodium in air, their fabricated structure could not survive removal from the vacuum chamber. Later the direct deposition of more stable atoms was explored, with extensive demonstrations in chromium [2]. The structures fabricated with such direct deposition techniques are limited to atoms with readily accessible optical transitions for interaction with laser fields.

By contrast, lithographic techniques can be used to make nano-scale patterns with a much wider range of materials because the patterning is done with atoms that are different from the eventual fabricated material. The only requirement on these materials is the ability to create resistance or acceptance to an appropriate chemical etch. Thus, very many materials can be patterned for fabrication.

Atom lithography with a positive resist works by destroying the chemical bonds in a layer of polymeric molecules of self-assembled monolayers (SAM's), then dissolving the damaged molecules, and finally etching the exposed area. Using the metastable $2^3$S state of helium (He*) is ideal for this because its internal energy of 20 eV is higher than any other metastable atom. Thus it is most effective for exposing a resist with minimum dosage and therefore shortest exposure time and thus minimum restrictions on the atomic beams and laser control [3].

The use of He* to make such chemical modification to a surface resist for later etching was first reported in Ref's. [4], using the shadow of a mechanical mask for patterning. Soon afterward, metastable Ar was also used [5]. The first use of optical fields to steer and channel He* atoms was reported in [6]. These fabricated arrays have intrinsic nanometer dimensions since the characteristic scale of optical interferences is $\lambda/2$ [3].

We have performed neutral atom lithography using a bright beam of He* that is collimated with the bichromatic force [7], followed by a few optical molasses velocity compression stages. Because bichromatic collimation makes such an intense He* beam, our exposure time is measured in minutes instead of hours. We have observed the focusing and channeling of the He* beam by the dipole force the atoms experience while traversing a standing wave of $\lambda$ = 1083 nm light tuned 490 MHz above the $2^3S_1 \rightarrow 2^3P_2$ transition.

The He* beam originates from a reverse flow DC-discharge source [8] with a slightly supersonic longitudinal velocity distribution centered near 1100 m/s and is about $\pm$200 m/s wide. The bichromatic force region is followed by a "booster" molasses stage with large detuning, and then an ordinary Doppler molasses to bring the atomic beam divergence down to nearly $\pm$1 mrad thus delivering a flux of $\sim 1.5 \times 10^9$ atoms/s-mm$^2$ to our sample [9].

Our samples are built on commercial, single crystal silicon wafers that have a 200 Å layer of gold evaporated onto their [100] surface over a 5 Å chromium adhesion layer. The SAM is assembled onto the gold surface by submersion in a 1mM solution of nonanethiol in ethanol overnight. The long chain molecules orient themselves with their hydrophobic heads bound to the gold substrate and their long-chain hydrophillic tails sticking out into the solution.

The beam of He* atoms is focused into lines by a standing wave field of $\lambda$ = 1083 nm light tuned $\sim$ 490 MHz above atomic resonance (atoms attracted toward the nodes). The etching process transfers the pattern of the focused He* atoms to the wafer and the results are shown in Fig. 1. These samples have an edge resolution of $\sim$80 nm as measured with an atomic force microscope. This seems to be limited by domain granularity of the gold layer and the etching

process. This method of neutral atom lithography is analogous to ordinary resist-based technologies that are used in most conventional lithography processes.

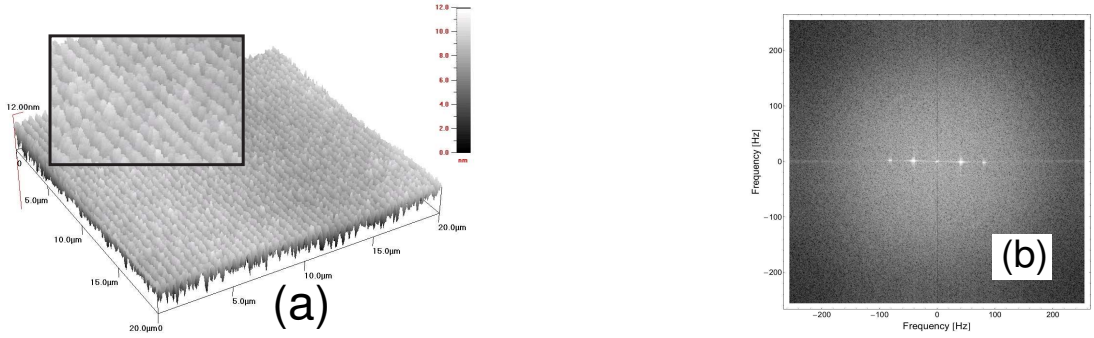


Fig. 1. (a) AFM scan of a patterned wafer. The unfocused peak dosage was 3 $\times 10^{12}$ atoms/mm$^2$ during the 36 minute exposure. The intensity of the light mask beam used for patterning was 5.93 W/cm$^2$, corresponding to $\sim$4 $\times$ the 1.48 W/cm$^2$ threshold for the focusing regime. It is cut in the middle by the substrate, as on the left side of Fig. 3 in Ref. [3]. Thus its width is 3 mm along the surface perpendicular to its k-vectors (twice the waist) and the atoms travel $\sim$ 330 $\mu$m through half of it before hitting the substrate. This image has a 5 point smoothing but still clearly shows both the graininess of the original gold coating. (b) 2-D Fourier transform of the AFM Scan.

Our fabrications have been reliable and repeatable, sample after sample, over a period of months. In a standing wave arranged to focus the He* into lines separated by $\lambda/2$ on the sample, our lines cover the entire exposed length of the substrate, about 3 mm. They are 3 mm long, corresponding to about twice the beam waist of the laser standing wave. Thus there are $\sim 6 \times 10^3$ lines of length $\sim$2800 $\lambda$ [9].

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