Neutral Atom Lithography with a Bright Metastable Helium Beam

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Abstract

We have performed neutral atom lithography using a bright beam of metastable 2^3S_1 Helium (He*) that is collimated with the bichromatic force and subsequent optical molasses. Incident He* atoms damage the molecules of a monolayer of resist by depositing their 20 eV of internal energy in a pattern determined by a mechanical or "optical" mask, and a chemical etch then imprints this pattern on a 20 nm underlying gold layer. We make lines separated by λ/2 that cover the entire 3 × 3 mm of the exposed substrate. These results agree with our numerical simulations of the experiment.

Bright He* Beam

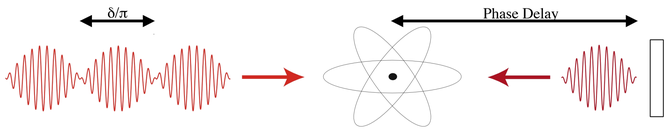
COLLIMATION

Intuitive Approach to the Bichromatic Force

Basic Ideas:

- Control momentum exchange between light field and atom by timing of counter-propagating pi pulses (phase condition).
- De-excitation process is stimulated not spontaneous emission.

The Pi-pulse model

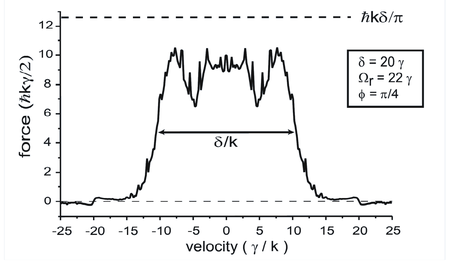


Pi-pulse condition: $\Omega_r = dE_o/\hbar = \pi\delta/4$ and s~2(δ/γ)²

Averaged value → $F = \frac{\hbar k\delta}{\pi} >> \frac{\hbar k\gamma}{2}$ (huge compared to scattering force)

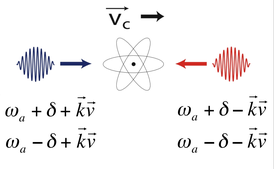
Magnitude of the Bichromatic Force

The force profile is calculated by numerical evaluation of the Optical Bloch Equations



Shift the Center Velocity of the Force

For moving atoms the counter-propagating pi-pulse trains need to be detuned by *kv* to compensate for the Doppler shift.



$\vec{k}\Delta\vec{v} = \Delta\omega$

Optical Molasses Stages for Final Collimation

Bichromatic collimation results in a beam divergence of 9 mrad. Final collimation to 1.1 mrad divergence is achieved with several Doppler molasses stages.

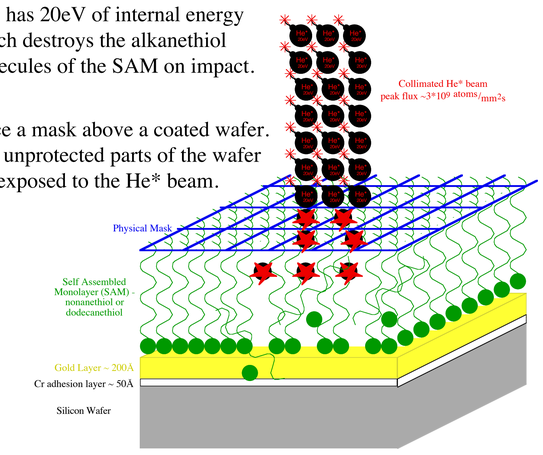
All of the collimation stages use only 8.2 cm of the atomic beamline.

Nanoscale Patterning

LITHOGRAPHY PROCESS

He* has 20eV of internal energy which destroys the alkanethiol molecules of the SAM on impact.

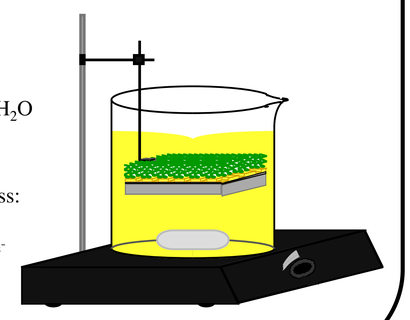
Place a mask above a coated wafer. The unprotected parts of the wafer are exposed to the He* beam.



Damaged SAM molecules leave underlying Gold layer susceptible to a standard wet chemical etch [2]:

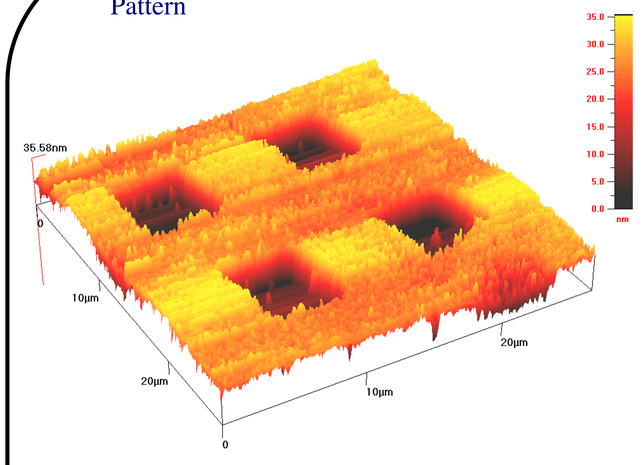
1M	KOH
0.1M	$K_2S_2O_3$
0.01M	$K_3Fe(CN)_6$
0.001M	$K_4Fe(CN)_6 3H_2O$

Electrochemical Etch Process:
Metal Oxidation:
$Au^0 + 2S_2O_3^{2-} = Au(S_2O_3)_2^{3-} + e^-$
Reduction of Oxidizer:
$Fe(CN)_6^{3-} + e^- = Fe(CN)_6^{4-}$

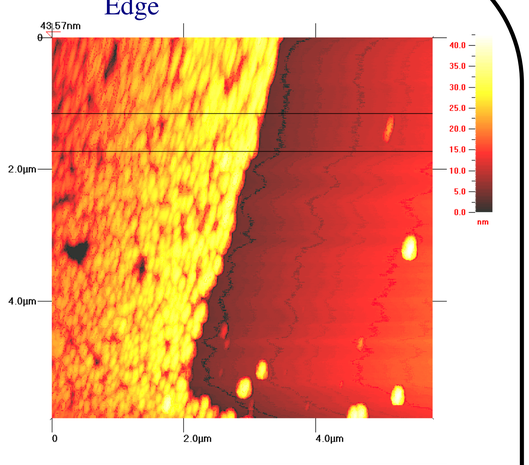


PHYSICAL MASK:

Pattern

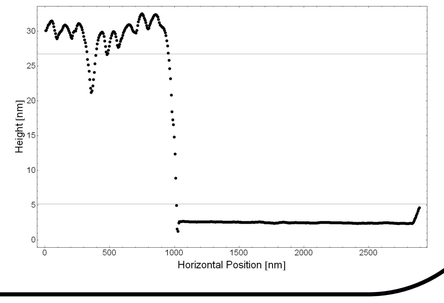


Edge



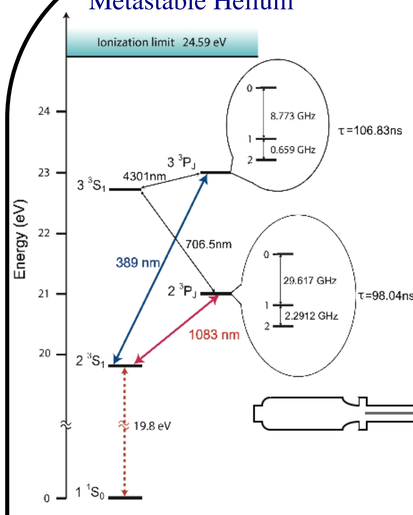
Results

- Edge resolution of 80 nm.
- Dosage at beam peak: $3*10^{12}$ atoms/mm²
- Assuming ~10 a_o^2 effective area of alkanetiol molecule on surface, we have an exposure dose of 0.59 He* atoms per resist molecule.

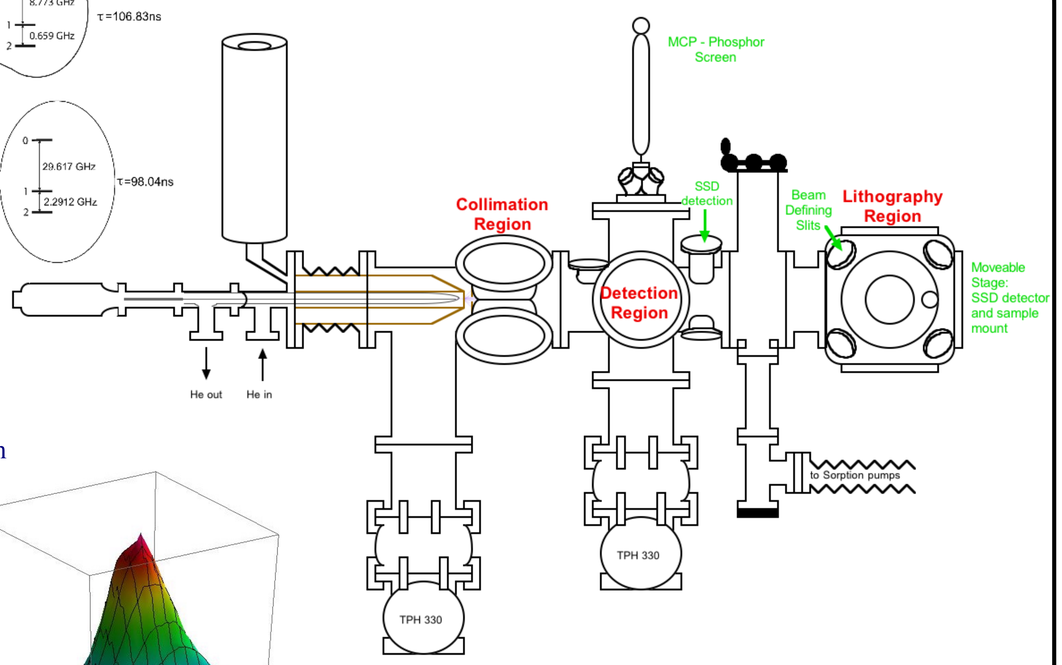


EXPERIMENTAL SETUP

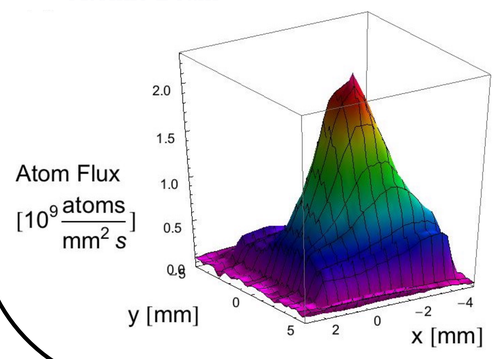
Metastable Helium



Experimental Chamber



Atomic Beam



The reverse flow DC discharge source produces He* atoms with a $v_{\bar{r}}$=1000 m/s and a flux of ~0.5*10¹⁴ atoms/sr s [1].

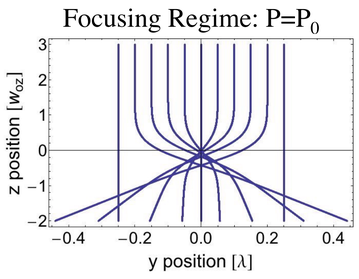
The detected signal corresponds to a peak current of $3*10^8$ aoms/s through an aperture of area 0.1 mm². The collimated beam has a full width half max of 3.5 mm at 33 cm from the source; and was measured to have a divergence angle of 1.1 mrad.

STANDING WAVE LIGHT MASK:

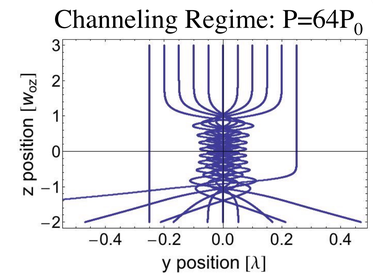
$$P_0 = \frac{\pi w_{ox} w_{oz}}{8} I_{focus}$$

$$I_{focus} = 5.37 \frac{m_{He^*} v_z^2 I_{sat} (\gamma^2 + 4\delta_{LM}^2)^2}{\hbar \delta_{LM} k^2 w_{oz}^2 \gamma^2}$$ [3]

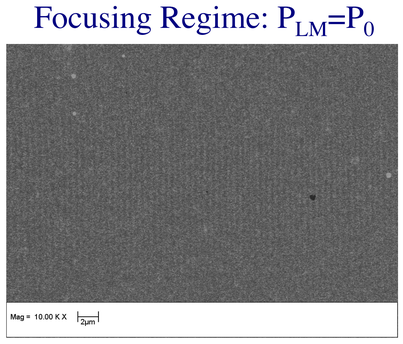
Focusing Regime: P=P₀



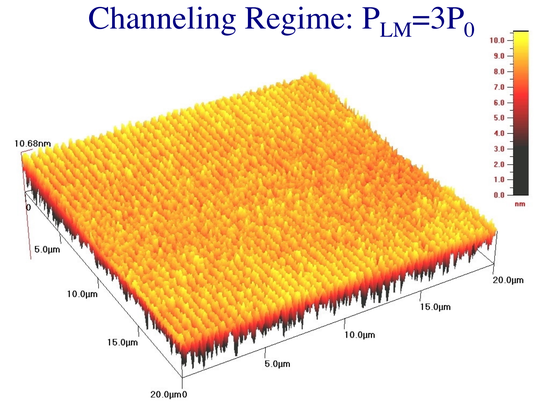
Channeling Regime: P=64P₀



Focusing Regime: $P_{LM}=P_0$



Channeling Regime: $P_{LM}=3P_0$



Results:

- Controlled the He* induced destruction of a SAM on an Au coated Si wafer with a standing wave light mask.
- Lines in the pattern were spaced λ/2 apart, as expected.

References:

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2. Y. Xia et. al. Chem. Mater. **7** 2332 (1995)
3. J. McClelland J. Opt. Soc. Am. B **12** 1761 (1995)

Further Reading:

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