Progress towards atom lithography on iron
E. te Sligte*, B. Smeets, R.C.M. Bosch, K.M.R. van der Stam, L.P. Maguire1, R.E. Scholten1, H.C.W. Beijerinck, K.A.H. van Leeuwen

Eindhoven University of Technology, Postbus 513, Eindhoven 5600 MB, The Netherlands

Abstract

We aim to apply atom optical techniques to iron to produce periodic magnetic nanostructures. Laser cooling has been observed experimentally, and calculations predict that a bright beam can be obtained with 200 μrad divergence. We expect to be able to laser focus this beam to feature sizes around 10 nm by the use of nanoscale mechanical beam masking and velocity selection via a supersonic source. In separate calculations, we have modelled surface diffusion of the atoms during deposition using a kinetic Monte Carlo approach taking into account the Ehrlich–Schwoebel barrier. These calculations successfully explain anomalous broadening of structures observed in similar experiments on chromium [Anderson et al., Phys. Rev. A 59 (1999) 2476].

Keywords: Atom optical techniques; Magnetic nanostructures

1. Introduction

Atom lithography is a powerful method for producing nanostructures with a fixed periodicity over large distances. It uses the optical dipole force in a resonant standing laser wave to focus atoms onto a substrate. The first experiments involving deposition of sodium [1] and chromium [2,3] produced structures that could only be probed topographically. We aim to use atom lithography to create periodic arrays of ferromagnetic lines or dots. This would create a length scale on the nanometer level accessible by magnetic probing methods, and additionally provide a new angle of approach to the scientific investigation of magnetism at such small length scales.

The basic principle of atom lithography as implemented by us is shown in Fig. 1; a more detailed description can be found in Ref. [4]. In our experiment, the atoms emerge from a supersonic beam source. They are collimated by transverse laser cooling to create an intense, parallel beam...
downstream. There, the atoms encounter a nearly resonant standing laser light field, which induces an optical dipole in the atoms. For laser frequencies below resonance, the dipole is parallel to the momentary electric field, and the atoms are drawn towards higher intensity. Near the antinodes, the potential thus created is approximately parabolic and the standing wave functions effectively as an array of lenses. We intend to use mechanical beam masks to shield the nodes, resulting in better focusing and, especially, background-free deposition. The period of the structures thus created is determined by the lens spacing in the standing wave, which is known with interferometric accuracy.

In this paper, we will give an overview of our progress towards the goal of periodic magnetic nanostructures, discussing first our efforts to laser cool atomic Fe. We will proceed to briefly describe laser focusing of Fe atoms by a standing wave. Thirdly, we will describe a model for diffusion of the atoms on the surface and its influence on the feature sizes that can be attained. We will conclude with an outlook.

2. Experiment

When focusing atoms, as when focusing light, the divergence and finite source size of the incoming beam cause broadening of the focus. For the structures to be small with respect to their given period, we must limit the beam divergence. The use of laser cooling is nearly unavoidable, as beam collimation by aperturing leads inevitably to drastic flux losses. Hence, we apply Doppler cooling [5] to limit the divergence of our beam. Doppler cooling uses two counterpropagating laser beams tuned below resonance. An atom that has a component of its velocity along the laser beam axis experiences different Doppler shifts for both laser beams. The atom will scatter more photons from the laser beam propagating opposite to its velocity, and fewer from the other beam, resulting in a net force contrary in direction to the atomic motion.

For Fe atoms, Doppler cooling is quite hard to achieve for two reasons. Firstly, the best available optical resonance is at 372 nm. A continuous wave UV laser system is required, but not available commercially. Secondly, the resonance is not a closed electronic transition. Rather, the atoms have a
chance of about 1 in 243 for every photon scattered to decay to a metastable state that is not resonant with the laser. This means that we must modify our setup so that the atoms scatter as few photons as possible.

We have performed classical as well as quantum mechanical Monte Carlo simulations of the laser cooling process. The results of one such simulation are shown in Fig. 2. Theory predicts that Doppler cooling functions optimally for a detuning of $\Delta = G/2$, where $G$ is the natural linewidth of the transition. For Fe, this corresponds to a minimum velocity spread of 0.096 m/s. Assuming a beam moving at 1400 m/s, this results in a full beam divergence of 140 µrad. Our simulations predict that it is possible to closely approach this limit, but only at the cost of scattering a large number of photons. Given the leak rate of the transition, we found that limiting the average number of photons scattered per atom to 100 resulted in an acceptable atom loss of about one-third. With this added condition, the best results were predicted at a detuning of one linewidth, and an intensity of 31 µW/mm². The beam divergence under these circumstances is 200 µrad.

Experimentally, we have built a supersonic Fe source using Fe vapour as a seed gas in a supersonic Ar expansion, as described in detail in Ref. [6]. We have also constructed the necessary UV laser system capable of producing over 500 mW of 372 nm light by frequency doubling a Ti:S laser. The laser is frequency locked to within 2 MHz of the desired frequency using polarization spectroscopy on a hollow cathode discharge. A more extensive description can be found elsewhere [7].

We have demonstrated laser cooling, as illustrated in Fig. 3. The figure depicts fluorescence images taken 1 m downstream from the laser cooling section. The image with laser cooling clearly shows a narrower, brighter distribution of atoms. Additionally, we have seen up to a 30% increase in beam flux using a mass spectrometer 1.8 m downstream from the cooling section as a result of laser cooling. This is the first evidence of laser cooling on any ferromagnetic element. Further work is under way, including a determination of the exact leak rate [8] and optimization of the laser cooling process.

We have also simulated laser focusing of the laser cooled atomic beam using both a semiclassical dressed-state model and a fully quantum mechanical atom wave diffraction model. The dressed state model [5] considers the Hamiltonian of the whole atom-laser beam system as a potential that the atom moves through as a classical point particle. The dressed state simulations yield atom distributions as shown in Fig. 4 for various incoming atom beams. As can be seen, the width of the distribution

![Fig. 2. Simulated transverse velocity distribution of a laser cooled Fe beam for laser intensity 31 µW/mm² and detuning $\Delta = - G$. The velocity distribution has been normalized relative to initial velocity distribution.](image-url)
increases directly with increasing beam divergence. The plots within one subplot show the effect of varying the axial velocity distribution of the incoming beam. The middle plot represents circumstances feasible using Doppler cooling. The deposited linewidth decreases from a full width at half maximum (FWHM) of 15 nm for a thermal beam to a FWHM of 8 nm for our supersonic beam. The full quantum mechanical simulations show that diffraction effects prohibit further focusing of the atoms.

![Figure 3](image1.png)

**Fig. 3.** Experimental demonstration of laser cooling of Fe. Top, fluorescence images taken downstream from laser cooling section with laser off (left) and on (right). Bottom, sections through both images. The laser field clearly narrows and intensifies the atom distribution.

![Figure 4](image2.png)

**Fig. 4.** Laser focusing for various atom beam velocity distributions, as simulated for laser detuning 5000 Mrad/s, and power 50 mW over $10 \times 200 \mu m^2$. The slits in the beam masks are 100 nm wide. The vertical location of masks is irrelevant; they are shown for heuristic purposes only.
Our findings on laser focusing of atoms are in line with those found at NIST in similar simulations for chromium atoms [9]. Experimentally, however, the structures deposited at NIST have never been less than about 30 nm wide. Being able to find no fault in the atom optical simulations, several groups have turned to atomic surface diffusion as the driving mechanism for this feature broadening. Both thermally activated surface diffusion [10] and impact cascade activated surface diffusion [11] have been investigated.

Models based on simple thermal surface diffusion could not reproduce the observed lack of temperature dependence found in broadening. Impact cascade diffusion fails to explain the observed dramatic substrate dependence of the features deposited [12]. This has led us to propose a model based on Ehrlich–Schwoebel (ES) barrier limited diffusion. The ES barrier limits diffusion from one terrace to another, as the activation energy for such a process is higher than that for diffusion across a terrace. This implicitly assumes that the structures deposited are crystalline to at least a moderate degree.

We have performed one-dimensional kinetic Monte Carlo simulations [13] during which atoms were free to diffuse across a terrace, but had a reduced diffusion coefficient from one terrace to another. Results of this simulation are shown in Fig. 5, and compared to the experimental results from Ref. [9]. As can be seen, the agreement is good. Furthermore, simulations at different temperatures do not affect the resulting structures due to the temperature independence of the diffusion inhibiting effects. We therefore believe that we have found a working model for the diffusion broadening of the structures.

3. Conclusion

In this paper we report on significant progress towards the production of periodic nanomagnetic structure arrays. We have achieved the first laser cooling of a ferromagnetic element. We have also
found the most satisfactory explanation to date of the anomalous structure broadening observed at NIST, based on Ehrlich–Schwoebel barrier limited surface diffusion. Work in the near future will focus on deposition of atomically clean Fe layers on substrates, and patterning them using mechanical and optical beam masks.

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References