Summary

Since the beginning of the 1980’s many experiments have been performed where the motion of atoms is controlled with laser light. This research has led to the exploration of an entirely new field of physics, called atom optics. In atom optics, the role of matter and light is interchanged compared to conventional optics. Where in conventional optics light is reflected and focused with mirrors and lenses (matter), in atom optics light fields are used to control the motion of atoms. This control of atoms is based on the interaction of the atoms with the light field. In the process of absorption and emission of photons, momentum is exchanged between the atom and the light field, resulting in a light force on the atom. With the use of this light force, the motion of atoms can be manipulated in a very precise way. By slowing atoms down to very small velocities, atomic samples with extremely low temperatures, on the order of a few microkelvin above absolute zero, can be achieved. Another use of atom optics is the manipulation of atomic motion with light to create extremely small structures. This application of atom optics is called atomic nanofabrication. In this thesis atomic nanofabrication with metastable helium is investigated. The goal of the research is to find the maximum resolution and the smallest structures that can be realized when the motion of metastable helium atoms is controlled with standing waves produced by 1083 nm laser beams.

In Chapter 1 the basic principles of atomic nanofabrication are outlined and two processes are distinguished. In a direct deposition process, the flux of an atomic beam is spatially modulated with a mask, and the atoms incident on the sample surface grow a structured pattern. Another atomic nanofabrication process is atom lithography. In this process, the incident atoms do not form a structure on the surface, but they damage a resist layer. This resist layer protects the surface underneath, a gold film, in an etching process. When the sample is
exposed to the etch solution, the damaged molecules of the resist layer and the gold film underneath are dissolved, and a structure is written in the gold film. The flux of the atomic beam is spatially modulated with a mechanical mask (a grid) or an optical mask. The optical mask is formed by a standing-wave light field which frequency closely matches an optical transition of the atom. The atom interacts with the light field, resulting in a force that focuses the atoms in the light field. In case of a one-dimensional (1D) standing wave, that acts as an array of cylindrical lenses, the atoms are focused into lines on the surface. With a 2D optical mask, the atoms are focused into dots, and a dotted pattern is created. Also in this chapter, an overview of atomic nanofabrication experiments in other groups is discussed.

Chapter 2 describes the experimental setup and procedures of atom lithography with metastable helium. The apparatus includes a vacuum setup and laser systems. In the vacuum chamber a beam of metastable helium atoms is created in a DC discharge, where the atoms are transferred from the $1^1S_0$ ground state to the $2^3S_1$ metastable state. This beam is optically collimated in two dimensions with laser light. By collimating the atomic beam, the transverse velocity spread of the beam is reduced, and the beam flux is increased. Before hitting the sample, the collimated beam passes a standing-wave light field that forms the optical mask. The light of the optical mask has a frequency that is slightly higher than the $2^3S_1 \rightarrow 2^3P_2$ optical transition frequency in the helium atom and has a wavelength $\lambda = 1083 \text{ nm}$. The samples are made of silicon and contain a gold film with a thickness of about 30 nm. On top of the gold film a Self-Assembled Monolayer (SAM) is deposited, that forms a resist layer in an etching process. When the metastable helium atoms hit the sample surface, the internal energy of the atom (19.8 eV) is used to damage the SAM molecules. After the exposure to the atomic beam, the damaged molecules and the gold layer underneath are removed in a wet-etching process.

To investigate the limits of nanolithography with metastable helium, the motion of the atoms through a standing wave light field is calculated in Chapter 3. Two different models are used to simulate the atomic motion. A conventional model, that derives the dipole force experienced by the atom from the light potential, is compared with a more sophisticated model that also includes the velocity spread of the atomic beam. Also, two regimes are discussed for guiding the atom in the light field, a focussing regime, and a channeling regime. In the focussing regime, the atoms are focused once in the standing wave, while in the channeling regime the atoms oscillate around the potential minima of the light field. The calculations show that the smallest structures are obtained in the channeling regime. In this regime, simulations with the conventional dipole force model predict structures with a Full Width at Half Maximum (FWHM) of about 100 nm. The model that includes the velocity of the atoms shows that
structures with a FWHM on the order of 40 nm are attainable. This result is in agreement with Monte-Carlo wave-function calculations.

The first experimental results are presented in Chapter 4. By exposing the samples to a beam of metastable helium atoms an image of a mechanical mask with 1000 lines/inch is made. The resulting step-edge width, defined as the width where the profile height ascends from 10% to 90% of the total height, is about 40 nm. This width is determined by the isotropic etch process, that prevents a steeper side wall inclination of 40°. In another experiment, with a 1D standing wave light field, a line pattern is created with a line separation of \( \lambda/2 \) (= 542 nm). The average FWHM of the structures is 100 nm. For the protective resist layer two alkanethiol molecules are used as a SAM, nonanethiol and dodecanethiol. For optimum results samples with the nonanethiol SAM have to be exposed and etched for eight minutes. The dodecanethiol SAM requires exposing and etching times of ten minutes.

The creation of more complex structures with 2D optical masks is presented in Chapter 5. The intensity pattern of the 2D light field depends on the polarization of the individual interfering beams. In the experiments both a linearly polarized light field, perpendicular to the plane of incidence, and a circularly polarized light field are used as an optical mask. Numerical calculations have been performed to simulate the atomic motion through optical masks with these polarizations. With the linear polarized light field, a dotted pattern is created with a \( \lambda/\sqrt{2} \) (= 766 nm) separation, which agrees with the calculations. The results of the circularly polarized light field show a line pattern, with a line separation of \( \lambda/\sqrt{2} \) (= 766 nm). These results can not be explained from theoretical considerations.

In Chapter 6 some concluding remarks are made about the research results. A major problem of metastable helium atom lithography experiments turned out to be the lack of reproducibility. The chemistry involved in the lithography process, in both the preparation and the etching of the samples is not well understood. The graininess of the gold, that shown clusters of about 20 nm puts a limit on the obtainable feature size. Experimentally, structure widths of 100 nm were the best results. However, also in other nanolithography experiments, structure sizes much smaller than 50 nm have not yet been realized. Moreover, arbitrary structures have not yet been reported, and with the current atom lithography techniques the creation of such structures is not straightforward. On the other side, with conventional optical lithography the creation of complex structures is possible. It is therefore expected that the future of atom lithography will be in the area’s that are unaccessible for optical lithography, such as the creation of structure doped materials.