Permanent magnetic atom chips

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Chapter 4

The atom chip

We describe our atom chip which has been designed for the production and manipulation of a BEC near the surface of the magnetic material [14]. It is the first ever applied atom chip based on in-plane magnetized permanent magnetic materials [10, 61, 62]. These magnetic films are well suited for making tight and stable trapping potentials up to a few 100 µm from the surface. To date, most atom chips use lithographically-patterned current carrying wires to manipulate atoms with a magnetic field. Large, macroscopic guides have been created with both permanent magnets [1, 4] and current-carrying wires [19, 63, 64, 65], but guiding atoms with smaller magnetic structures seems to be very promising.

Atom-chip experiments seek to exploit the close proximity of the atoms to the field-producing elements to explore new regimes created by these potentials. With the atoms close to the magnetic structures, the magnetic-field gradients and curvatures the atoms experience can be extremely high. Hard magnetic films have great potential [66, 11] as atom chips and have several advantages over current carrying wires.

In this chapter we present the magnetic material used for our structures and films. Then we discuss how a self biased Ioffe Pritchard trap is created on an atom chip made out of permanent magnetic material. Finally we describe a new atom chip containing arrays of traps using thin films.

4.1 Atom chip holder

The atom chip assembly can be seen in Figure 4.1 (a). The assembly supports the chip, two Rb dispensers, a halogen lamp used for baking the UHV chamber and a thermocouple used to monitor the temperature close to the chip during the bake out. Temperature monitoring is essential because the magnetic material has a baking limit of 170 °C and exceeding this temperature would cause demagnetization of the magnetic structures. Remagnetizing them in situ is practically impossible because they have to be placed in a very high magnetic field which we
can not produce close to our setup. The whole assembly is inserted from above into the science chamber and is mounted on a single CF40 flange which contains ten 7 A electrical feedthroughs which supply current to the dispensers and the halogen lamp. The atom chip is fixed with two small non-magnetic clamps on a plate. This atom-chip holder is fixed with four rods on a ring ('bridge'), placed in the 6-way cross chamber. Four more rods connect the bridge to the feedthroughs. The rods are important for the height and angle positioning of the holder. The whole assembly is then fixed with four rods into a pair of groove grabbers (*Kimball physics*, multi-CF Groove Grabbers, MCF-275-GG-CAO-1 A), mounted on the flange.

In constructing the atom chip assembly, care is taken to make sure the components are non-magnetic and precisely aligned and to use materials compatible to a UHV environment. The atom chip holder is aligned with threaded rods and held together with screws. All the rods and screws used in the vacuum are made of a non-magnetic stainless steel and are vented down their centers to allow air to escape from the bottom of their holes. For the Rb dispensers we use copper wires, 1 mm diameter. The wires are kapton isolated so that the current does not flow through the atom chip holder. Kapton, also known as polyimide or vespel, withstands temperatures to 250 °C and is good at $10^{-11}$ mbar.

The chip has a very simple configuration. This is one of the advantages over current carrying wires atom chips. It consists of two small (mm scale) magnetic structures. The two microstructures are attached to the mirror with a UHV compatible glue (*Caburn UHV Glue-H27D Electrically Conductive Silver Epoxy*). This glue is good to $10^{-11}$ mbar and is bakeable to 370 °C. These structures provide the magnetic field for trapping the cold rubidium atoms. Their design is discussed below.

### 4.2 Selection of the magnetic material

In permanent magnetic atom chips the cold atoms are trapped in the magneto-static ‘stray field’ generated by the permanent magnets, which, when properly designed, do not require external fields. The stray field determines the depth of the traps which should be on the order of 0.1 - 1 mT.

The application of hard magnetic film poses specific material requirements. The first requirement is obviously a high magnetization in order to effectively generate the strong field gradients. However, magnetic materials tend to break up in domains exactly as a means to reduce the stray field that it produces. This demagnetization problem can also be caused by the external fields used for loading the atoms into the traps. A second requirement is therefore that the material has a high coercivity.

Since the most exciting project for atom chips is the possibility to integrate many microscopic atomic devices on a single chip, the material should be suitable
4.2. Selection of the magnetic material

Figure 4.1: The atom chip holder: (a) The complete setup. The bridge and the Rb dispensers are visible. (b) The head of the atom chip holder and the aluminium mirror. (c) The arrow indicates the direction of the magnetization M of the magnetic structures glued on the mirror.
for preparation as a film. The magnetic fields produced by such a thin film structure scale with its thickness. In order to produce a large enough stray field at a distance of a few $\mu$m from the surface with a line width of few micron, the material thickness should be in the range of 100 nm to 1 $\mu$m.

In addition, the material should be corrosion resistant to allow micromachining or lithographic patterning. In order to avoid uncontrolled spatial variations of the stray field, the material must also be highly homogeneous, which puts severe constraints on these manufacturing processes. Finally, the material is used in ultrahigh vacuum, which means that the magnetization should survive a 24 hours bake out at 150°C.

The combination of high magnetization and high anisotropy limits the range of materials naturally to the strongest room temperature permanent magnets which are Nd$_2$Fe$_{14}$B, Co$_5$Sm and FePt alloys (see e.g. [67]). Among these, the hard magnets Co$_5$Sm and Nd$_2$Fe$_{14}$B have excellent magnetic properties, but are difficult to grow as thin films. Moreover, Nd$_2$Fe$_{14}$B is unstable at bake out temperatures. The other candidates are the CoPt and FePt systems, where the latter has a higher magnetization and was therefore selected as the best material to meet our requirements. This alloy has been studied extensively, both in bulk [68, 69] and in thin film [70, 71, 72, 73, 74] structures since it combines high magneto-crystalline anisotropy with a high saturation magnetization $M_s$ [67] and corrosion resistance. FePt has a disordered face-centered cubic (fcc) structure at high temperatures (1300 °C) [75], and has a very high saturation magnetization but it is magnetically soft. The low temperature equilibrium structure on the other hand is face-centered tetragonal (fct or L1$_0$), in which the Fe and Pt order in an atomic multilayered structure with stacking in the [111] direction. This phase has a lower saturation magnetization but very high magneto-crystalline anisotropy and coercivity. It has been shown that annealing of either the fcc phase obtained from the melt [76] or as-deposited thin films produces noncrystalline composites of the two phases in which the nanocrystallites of the hard fct phase orient the surrounding soft phase by exchange coupling. This results in a material which combines high magnetization with isotropic hard magnetic behavior.

4.3 Design of the foil atom chip

4.3.1 Ioffe Pritchard trap design

The basic layout for an Ioffe-Pritchard (IP) trap (as described in Chapter 2) can be implemented with permanent magnets to create a micron sized trap for cold atoms. Two parallel magnetic strips produce a cylindrical quadrupole field in a similar way to the four current carrying bars in the IP trap. The axial field including the pinch fields are added by placing extra pieces of material at appropriate places, typically at the end of the strips. All dimensions can be scaled
4.3. Design of the foil atom chip

Figure 4.2: $y-z$ and $x-z$ plots of the calculated magnetic stray field for both magnetic structures (see Figure 4.2 (b)). a) and b) graphs show the trapping field of the upper structure, respectively c) and d) for the lower structure. Shown are contours of equal magnitude of magnetic field $B$, with a spacing of 5 G between the contours.

down ($< 100$ nm), resulting in large gradients and large curvatures.

The designs described here achieve trap depths higher than 0.5 mT, trap frequencies greater than 1 kHz and a non-zero minimum field so as to avoid spin flipping. The stray field of the patterns has been calculated using Mathematica [17] in combination with the Radia package [18].

Two in-plane magnetized strips produce a line of zero field above the gap between them, as explained in Chapter 2. A small modification of this design allows a self biased Ioffe Pritchard trap to be produced as a single piece of magnetic material. This leads to an $F$ like shape, as one can see in Figure 4.1. The bias field needed to lift the magnetic field minimum is given in this case by the stem of the 'F' and the extension of the upper long strip. These two extra parts also determine the trap depth. Thus the structure can create a self-biased IP trap. Plots of the calculated magnetic fields above the two structures are shown in Figure 4.2.
4.3.2 Fabrication of the ‘F’ structure

The F structures were made out of FePt foil produced by bulk metallurgic techniques [76]. This method is suitable for structures with sub-millimeter dimensions. The Fe$_{0.6}$Pt$_{0.4}$ alloy is made by arc melting in a purified Ar atmosphere. The melt is then cast into a water-cooled copper mould to get cylindrical samples with a diameter of 1.5 mm. These are sealed into evacuated quartz tubes and homogenized at 1300 °C for 3 hours after which they are quenched into ice water without breaking the quartz tube in order to produce fct grains in an fcc matrix. Subsequently the samples are annealed for 16 minutes at 580 °C in order to obtain the nano-composite FePt. A bar of this material was rolled into a 100 µm thick foil and then mechanically polished to 40 µm thickness. The in-plane magnetization loops of this compound, measured with a SQUID, are shown in Figure 4.3.

From this figure one can see that the ratio of remanent to saturation magnetization $M_r/M_s$ is about 0.8. The coercivity is about 0.2 T; much larger than the external field that we apply to manipulate the atoms (10 mT). Since saturation requires at least 3 T it is impossible to magnetize the sample in situ. It is therefore crucial that the material maintains its magnetization during the 150 °C vacuum bake-out. As Figure 4.3 (b) shows, the magnetization of the saturated sample that was baked at 170 °C for 24 hours decreased less than 5%.

Two slightly different, elongated, F-like samples (see Figure 4.1 (b)) were cut out of the 40 µm foil using CNC controlled spark erosion. The diameter of the wire used for cutting is 50 µm. After cutting, the damaged surface layer of the outer edges of the F-shaped sample was removed by mechanical polishing. Two such samples were mounted on the aluminium mirror as shown in Figure 4.1 (b). The structure was designed as one single piece to avoid positioning problems while gluing the structure onto the mirror. The smallest size of the gap between the two hands of the big F shape is determined by the diameter of the wire that we used to cut the sample. In the optimization we only used one gap size and tuned the shape and the dimensions of the pattern according to the thickness of the foil.

The calculated trap frequencies for the lower structure (see Figure 4.1(b)) are 51 Hz in the axial direction and 6.8 kHz in the radial direction with a trap depth of 1.1 mT (760 µK). Finding the trap depth was not trivial. It is determined by the lowest saddle point in B that can be reached from the trap minimum on an ascending path. In general, this saddle point is not located in one of the cartesian coordinate planes through the minimum. Thus, one must search for this saddle point in three dimensions with sufficient spatial resolution, for risk of undersampling. A more detailed description on how to search for it can be found in [77]. For the experiments we used the upper structure, which has a higher trap depth, 3.3 mT (2.3 mK). For this structure the calculated frequencies are 34 Hz axially and 11 kHz radially.
Figure 4.3: Magnetization loops of a 40 µm foil of nanocrystalline FePt with in-plane magnetization, before (a) and after (b) baking, at 170 °C for 24 hours.
Finally, the samples were magnetized in a 3 T field oriented along the $y$-direction (see Figure 4.1 c) before they were mounted on the atom chip holder and inserted into the vacuum chamber.

### 4.4 Arrays of Ioffe-Pritchard traps

In this section we describe the design of another interesting application of permanent magnetic materials and atom chips: the possibility to create a large array of traps on one chip. Such arrays should enable one to move atoms from one trap to another as in a shift register which is useful for quantum information processing. This requires traps on the micrometer scale, implying films with (sub-)micrometer thickness. According to our calculations a film thickness of 250 nm is satisfactory for making sufficiently tight magnetic trapping potentials.

#### 4.4.1 Design of the arrays

As described in Chapter 2, each array consists of a series of magnetic strips, magnetized in plane, all with the same geometry but with different parameters, $w, s, d$ and $l$. Examples can be seen in Figs 4.7 and 4.8.

The working principle of this design can be explained as follows: $(n-1)$ cylindrical quadrupoles are formed between $n$ equally long strips. As one can see neighboring strips are shifted with respect to each other by a constant step, like a staircase (see Figure 4.7). As a result, for every pair of neighboring strips the upper strip extends a little to the right of the pair, while the lower strip extends to the left. These extended pieces of magnetic material pinch off the ends of each trap and produce the axial field. This results in a trap formed between each pair of neighboring strips with a nonzero field minimum. We calculate that the trap depth increases with the increase in the size of these 'end caps'. A plot of the magnetic field contours reveals a periodic array of magnetic field minima as shown in Figure 2.6. The trap frequencies calculated for the central trap are 110 kHz in the radial direction and 1.5 kHz in the axial direction. The traps are 1.4 mT (980 µK) deep and their minima are formed 4 µm away from the surface.

#### 4.4.2 Fabrication of the arrays

The second generation chip is based on FePt film deposited on silicon. A thick film can be grown with vacuum deposition and can be structured using lithographic techniques in the micron range. A thin film can be grown in multi layers (up to several 10 nm). Here we used 250 nm Fe$_{50}$Pt$_{50}$ films, coevaporated by Molecular Beam Epitaxy (MBE) from Fe and Pt targets on a rotating Si substrate at 350 °C.
Figure 4.4 shows the X-Ray diffraction (XRD) patterns of the sample deposited at 350 °C, before and after annealing. It can be seen that the peaks of the as-deposited film are broadened compared with the film after annealing. This indicates that some intermediate cubic structure, L12-type cubic crystal structure, was formed [68]. This structure can be also called the ordered fcc phase, in which there is some atomic ordering but not strong enough to form the tetragonal phase. After annealing the ordered fct phase was formed. SEM and optical microscopy show that the surface of these films is free of micro-cracks.

The samples are post-annealed in vacuum at various temperatures in order to get hard magnetic properties. Figure 4.5 shows the magnetic properties of the film as a function of annealing temperature. From this figure one can see that the best magnetic properties (optimum $M_r/M_s$) are: $M_s = 750$ kA/m, $M_r/M_s = 0.93$, $H_c = 0.83$ T for out-of-plane magnetization ($T_{anneal} = 450$ °C) and $M_r/M_s = 0.90$, $H_c = 1$ T for in-plane magnetization ($T_{anneal} = 500$ °C). These loops show that the magnetic properties of the films are comparable to the bulk material. A very desirable aspect of these results is that these films can be used for both in-plane and out-of-plane chip designs.

The films were patterned using e-beam lithography, with a hard negative photoresist (SU-8), to save the writing time. The patterning process consists of a few steps. First the surface is roughened using Ar plasma pre-etching in order to increase the adhesion of the SU-8 on the FePt surface. After spin-coating and pre-baking a 340 nm thick SU-8 photoresist layer was obtained. The desired pattern was written in this resist using a JEOL 6460 SEM equipped with a Raith
Figure 4.5: $M_r/M_s$ and $H_c$ of the FePt film as a function of annealing temperature (350 °C) of the as-deposited sample, (a) and (b). (c) shows the hysteresis loop of FePt film annealed at 450 °C for 3 minutes.
Quantum pattern generator. After writing, the resist is post-baked, developed to remove the non-exposed resist and hard-baked in order to harden the remaining resist layer.

The resist structure is subsequently transferred to the FePt layer by Ar plasma etching with an Oxford Plasmalab 80 Plus reactive ion etching system. The samples were etched for 7 minutes in order to slightly over-etch the FePt layer to get very clear patterns. Figure 4.7 (b) shows a typical FePt pattern and the cross section of one strip revealing a slope of the FePt edge of about 45°, with a roughness of about 50 nm, which is of the order of the nanocrystalline grain size. The etching rates of the SU-8 and FePt are almost the same (40 nm/min) but the photoresist layer is thicker than the FePt, and the inset shows that there is still a photoresist layer left on top of the FePt layer. It is straightforward to adjust the initial resist thickness in order to reduce this layer. Furthermore, since we will coat the final chip with a thin gold film to obtain a highly reflecting surface, the thin photoresist layer has little effect. Figure 4.7(a) shows an array of identical patterns on one chip, one of the advantages of the miniaturized permanent magnetic atom chips. As a final design of the chip we have chosen to pattern more arrays on one chip, as shown in Figure 4.8. This chip is a demonstration of the possibility to create many micro traps on one chip. It has not yet been used in the actual experiment, as the setup is still running with the bulk chip.

4.5 Conclusions

In this chapter we described how the magnetic properties of the material are changed to make it suitable for permanent magnetic structures on an atom chip.
Figure 4.7: Patterned 250 nm FePt film on Si substrate. (a) One array of strips. (b) The cross section of one strip of the pattern, as well as the edge roughness. SU-8 photoresist.

Figure 4.8: Patterned arrays of FePt film on Si substrate.
We also presented how permanent magnetic materials can be used to create microtraps for atoms, as well as the design and fabrication of the structures. High frequency traps can be created. By decreasing the sizes even stiffer traps can be formed. Single traps, or even arrays of them are easy to be made with permanent magnets.