J. Phys. D: Appl. Phys. **38** (2005) 4015–4020 doi:10.1088/0022-3727/38/22/003

# Perpendicularly magnetized, grooved GdTbFeCo microstructures for atom optics

**J Y Wang, S Whitlock, F Scharnberg, D S Gough, A I Sidorov, R J McLean and P Hannaford**

Centre for Atom Optics and Ultrafast Spectroscopy and ARC Centre of Excellence for Quantum-Atom Optics, Swinburne University of Technology, Hawthorn, 3122, Australia

Received 15 March 2005, in final form 26 August 2005
Published 7 November 2005
Online at stacks.iop.org/JPhysD/38/4015

**Abstract**
Periodically grooved, micron-scale structures incorporating perpendicularly magnetized $Gd_{10}Tb_6Fe_{80}Co_4$ magneto-optical films have been fabricated and characterized. Such structures produce a magnetic field having flat equipotentials and whose magnitude decays exponentially with distance above the surface, making them attractive for manipulating ultracold atoms in atom optics. The GdTbFeCo films have been deposited on a Cr underlayer on a silicon (100) wafer and on a grooved silicon microstructure using DC magnetron sputtering. The films are found to have excellent magnetic properties for magnetic atom optics applications, including high remanent magnetization, high coercivity and excellent homogeneity.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Atom optics involves the manipulation of atoms, particularly cold atoms, in an analogous way to the way light is manipulated in optics. High quality elements are needed in atom optics for many purposes including the reflection, diffraction, beamsplitting, trapping, storage and guiding of slowly moving atoms and atomic matter waves. The force commonly used to manipulate the atoms derives from the interaction between the induced electric dipole moment of the atom and the electric field gradient associated with a laser light field (see, for example [1]), but there are many advantages in exploiting the force that results from the interaction between the *magnetic* dipole moment of the atom and the magnetic field gradient near, e.g. a current carrying wire or a permanent magnetic structure [2]. These advantages include eliminating the need for a laser to generate the inhomogeneous light field, and the fact that the atoms can remain in the ground state so that the coherence-destroying process of spontaneous emission does not occur (see, for example [3]). Furthermore, permanent magnets have advantages over the use of current carrying wires to produce the magnetic field gradient that include eliminating the problems of heating, current instabilities and short and open circuits. It is likely, therefore, that many practical atom optics-based devices will incorporate permanent magnets.

A common requirement in magnetic atom optical devices is that the magnetic structure be periodic and have features on the scale of a micron. This is necessary to produce a 'hard' magnetic mirror where the magnetic field gradient is large enough so that the atom interacts with it over a short distance, and to use the periodic structure as the basis for a diffraction grating for atoms, requiring the period of the grating to be comparable to the de Broglie wavelength of the atom matter waves for reasonable diffraction angles and intensities. Difficulties in micromachining and magnetizing materials on this scale can be avoided by the use of magnetic films deposited on non-magnetic microstructures. In this paper we discuss the application of perpendicularly magnetized GdTbFeCo magneto-optical films widely used in the recording industry to the fabrication of periodic microstructures for magnetic atom optics. In the following section we outline the principles of magnetic atom optics with periodic structures and the use of grooved microstructures for producing a suitable magnetic field gradient, while in section 3 we describe the production and characterization of GdTbFeCo films and GdTbFeCo film-based microstructures with magnetic properties that are attractive for atom optics.

## 2. Principles of magnetic atom optics with periodic structures

A one-dimensional periodic array of magnets of alternating polarity or a one-dimensional periodically grooved magnetic structure produces a magnetic field pattern that is well suited to atom optics [2]. For such an array in the $xz$ plane with periodicity in the $x$ direction, the magnitude of the magnetic field depends on height $y$ above the surface as given by [3,4]:

$$|B(x, y)| = B_0 e^{-ky}[(1 - e^{-kb}) + \tfrac{1}{3}(1 - e^{-3kb})e^{-2ky} \cos 2kx + \ldots], \quad (1)$$

where $k^{-1} = a/2\pi$ is the decay length, $a$ is the period of the array, $b$ is the thickness of the magnets and $B_0$ is a characteristic magnetic field that is defined by the magnetization $M_0$ of the material. For an array of magnets of alternating polarity $B_0 = 8M_0$ (Gaussian units) and for a grooved structure $B_0 = 4M_0$. The factors $(1 - e^{-nkb})$ account for the finite thickness of the magnetic material. For heights $y \gg a/4\pi$ above the surface equation (1) reduces to

$$|B(x, y)| = B_0(1 - e^{-kb})e^{-ky}, \quad (2)$$

so that the magnitude of the magnetic field decays exponentially with height $y$. The $x$ and $y$ components of the magnetic field both vary sinusoidally in the $x$ direction, with a phase difference of $\pi/2$, so that they combine to produce flat magnetic equipotentials. When slowly moving atoms in positive or low field-seeking magnetic states ($mg_F > 0$, where $m$ is the magnetic quantum number of the state and $g_F$ the Lande g-factor) approach the surface of such an array, they are repelled by the increasing magnetic field strength and the array behaves as an atomic mirror (figure 1). The origin of the repulsive force is the magnetic dipole interaction that has potential $U_{int}(x, y, z) = -\boldsymbol{\mu}\cdot\boldsymbol{B}(x, y, z)$ producing the gradient force $\boldsymbol{F}_{grad} = \nabla(\boldsymbol{\mu} \cdot \boldsymbol{B}) = -mg_F\mu_B\nabla B(x, y, z)$, where $\mu_B$ is the Bohr magneton.

A periodic magnetic array in the form of a microstructure is also the basis of other atom optics devices. For example, it may be turned into an atomic matter wave diffraction grating by applying a small bias magnetic field normal to the microstructure surface to produce a spatial diffraction grating [2,5] or by applying an oscillating orthogonal magnetic field to create a temporal diffraction grating for atoms [6]. In addition, it is possible to generate magnetic microtraps and waveguides for low magnetic field-seeking atoms by applying appropriate dc bias fields to produce a series of magnetic field minima above the array surface [7]. A magnetic tube for transporting atoms may be formed from a cylindrically shaped periodic magnetic structure producing a radially varying magnetic field that guides atoms along the axis of the cylinder [8,9].

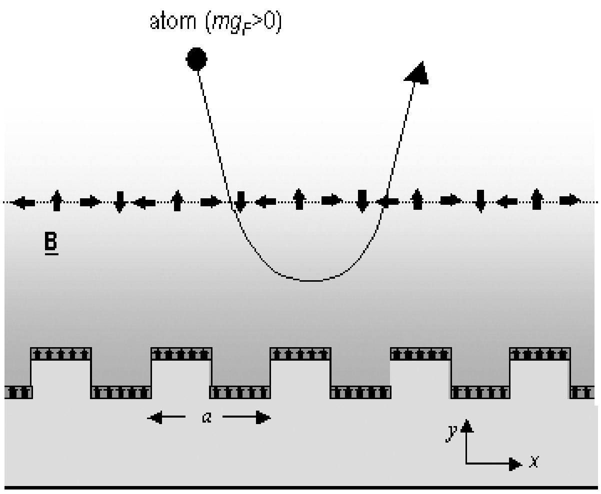


**Figure 1.** Reflection of atoms by a periodically grooved structure coated with magnetic film with perpendicular magnetic anisotropy.

The first atomic mirror to retro-reflect cold atoms was based on audiotape onto which a sinusoidal magnetic pattern of period 9.5 $\mu$m had been recorded [10]. Subsequently, sine waves with periods of around 15 $\mu$m were recorded onto floppy disks [11,12] and videotape [13]. These magnetic recording media magnetize in-plane, which limits the smallest period pattern that can be recorded and makes the recording of patterns of arbitrary shape difficult.

Magnetic mirrors have also been constructed based on periodic arrays of permanent NdFeB [14] and SmCo [15] magnets of alternating polarity. Although such magnets can produce large fields, they cannot be used to produce structures with micron-scale periodicities. In our magnetic atom optics programme, we have previously attempted to construct periodic grooved microstructures of ferromagnetic nickel, cobalt and alnico [16,17]. These microstructures were made by electron beam lithography followed by sputtering and electroplating processes that resulted in the entire grooved structure being made of the ferromagnetic material. In such a structure, these magnetic media also magnetize in-plane and have a strong preference for magnetizing parallel to the direction of the grooves. However, for magnetic atom optics, in order to produce the appropriate magnetic field distribution above the grooved surface of material that magnetizes in-plane, it is necessary to magnetize the structures at right angles to the groove direction. The structures failed to produce satisfactory results because of the difficulty in magnetizing the micron-scale protrusions between the grooves in this way. Magnetic force microscope (MFM) images revealed domain structure in the protrusions that indicated incomplete magnetization, and a magnetic field that fell off with a decay constant characteristic of the magnetic domain size rather than the periodicity of the structure [17].

Materials with a *perpendicular* magnetic anisotropy do produce the required magnetic field distribution when magnetized along the easy axis of magnetization. Microstructures comprising $Co_{0.8}Cr_{0.2}$ films on a non-magnetic grooved substrate and magnetized perpendicular to the array surface have been successfully used as magnetic mirrors [18,19]. For atom optics applications, however, the magnetic properties of $Co_{0.8}Cr_{0.2}$ films are inferior to those of GdTbFeCo magneto-optical films. In particular, the shape of the hysteresis loop indicates that the remanent magnetization is only about one quarter of the saturation magnetization and that the magnetic domains are not completely oriented, giving rise to magnetic inhomogeneities.

Magneto-optical thin films, such as ferrimagnetic (Gd,Tb)FeCo and (Dy,Tb)FeCo are widely used in magnetic recording and device applications due to their high perpendicular magnetic anisotropy, high saturation magnetization and large coercivity (see, for example [20]). We have fabricated periodically grooved microstructures based on $Gd_{10}Tb_6Fe_{80}Co_4$ films with perpendicular anisotropy and investigated their properties. Optimizing the magnetic properties of these films is crucial to successful device development and this demands careful preparation of the magneto-optical films and characterization of their properties. This paper reports investigation into these issues, and the results obtained indicate that the structures are highly suitable for atom optics applications.

Another magneto-optical material with perpendicular anisotropy that is a promising candidate for applications in atom optics is CoPt. CoPt films usually comprise multiple alternating layers of Co and Pt. Such a structure was recently magnetized with a view to producing atomic microtraps above its surface by ruling patterns of opposite magnetic polarity in the film using a magneto-optical recording technique [21]. We have used a similar magneto-optical recording technique with thicker TbFeCo magneto-optical films [17, 18, 22] but the quality of the recorded patterns was limited by demagnetization of the film adjacent to the writing laser during the recording process. Both CoPt and GdTbFeCo films appear to have excellent magnetic characteristics for atom optics, although one possible limitation of CoPt may be the relatively small thicknesses (of the order of 50 nm) that appear to be necessary if the perpendicular anisotropy is to be maintained.

Many atom optics experiments now involve miniaturizing and integrating atom optical elements on the surface of an 'atom chip' (see, for example [23]) and magneto-optical films will be useful in this technology as well. The use of permanent magnetic materials in atom chips offers potential advantages in overcoming the instability of the magnetic potential due to current fluctuations, as well as the problems mentioned earlier of heating from currents and short and open circuits. In our group, cold Rb atoms have recently been successfully trapped in a magnetic trap generated by a magneto-optical film above the surface of an atom chip [24]. In this case, no grooved structure is involved, but the magneto-optical film is similar to that used for the magnetic mirror microstructure discussed in this paper.

## 3. Film preparation and characterization

The GdTbFeCo films were prepared using a thin film deposition system (Kurt J Lesker CMS-18) capable of magnetron sputtering and electron beam evaporation. A composite target with a nominal atomic composition of $Gd_{10}Tb_6Fe_{80}Co_4$ and a chromium target were magnetron sputtered in the system. The magnetic properties of GdTbFeCo film vary considerably with composition (see, for example [25]). Briefly, the Curie temperature increases with the Co/Fe ratio, and the magnetization and coercivity vary not only with the Tb/Gd ratio but also with the amount of Co; the degree of perpendicular anisotropy depends on the Tb/Gd ratio and the rare earth to transition metal ratio. Film preparation parameters also influence the magnetic properties. The composition selected was expected to produce films with high remanent magnetization and coercivity and a Curie temperature of around 300 °C [26]. The effect of process parameters, such as argon gas pressure, substrate temperature, DC power and deposition time, on magnetic properties of the films was investigated, and the deposition conditions for preparing the best GdTbFeCo films within the capabilities of the deposition system were established using a statistical design of experiment methodology. The optimal deposition parameters were found to be an argon pressure of 4 mTorr, substrate temperature of 100 °C, dc discharge power of 150 W and a deposition time of 50 min. After optimizing the process parameters, a 140 nm thick chromium underlayer was deposited onto an Si (100) wafer and Si grating structures (periodicities $a = 1.5$ and 3 $\mu$m and groove depth of 0.5 $\mu$m) at a deposition rate of 10 nm min$^{-1}$, followed by a 150 nm thick GdTbFeCo film at a deposition rate of 3 nm min$^{-1}$. The base pressure of the chamber was less than $5 \times 10^{-8}$ Torr prior to introducing the argon gas and the target to substrate distance was 0.2 m. Finally, a 20 nm thick $Y_2O_3$ film was deposited onto the GdTbFeCo film as a protective layer using electron beam evaporation. The distance between the evaporation source and the substrate was 0.7 m.

Analysis of the film composition by inductively coupled plasma spectroscopy gives an atomic composition of $Gd_{9.6}Tb_6Fe_{80}Co_{4.4}$, which is close to the nominal composition of the target. It is well known that having a Cr underlayer can positively influence the surface morphology and improve the magnetic properties of magnetic films. To give some insight into the value of preparing the magneto-optical film on a Cr underlayer, a single-layer 140 nm thick Cr film and a single-layer 150 nm thick GdTbFeCo film were also prepared. All three films were prepared on Si wafers rather than grooved structures to facilitate the characterization. The surface features of the films were examined immediately after the samples were removed from the chamber by an atomic force microscope (AFM) operating in high resolution, semi-contact mode.

Figure 2 shows AFM micrographs of the surface morphology of the GdTbFeCo film on a Cr underlayer and the single-layer Cr film. The two films exhibit similar surface morphologies. Both are dense and their surfaces are smooth. The grain shape on both surfaces is found to be round, with an average grain size of approximately 40 nm. The single Cr layer possesses a slightly larger grain size and is a little rougher than the GdTbFeCo film on a Cr underlayer. By contrast, GdTbFeCo films deposited directly onto Si wafers have rougher surfaces and larger grain sizes ($\geqslant$50 nm). The smaller grain size of the GdTbFeCo films when deposited on a Cr underlayer may result from the enhanced surface roughness of the underlayer, suggesting that it aids the fabrication of dense GdTbFeCo films with smaller grain size and smoother surface.

Figure 3 shows MFM micrographs of the domain structure of the same film as in figure 2 made by scanning at a height of 100 nm above the film surface. In the unmagnetized state (*a*), a labyrinth of domain patterns with smooth surface contours can be clearly observed. These are typical of GdTbFeCo magneto-optical thin films with large perpendicular anisotropy. In the magnetized state (*b*), there is no domain structure visible, indicating that the film has excellent magnetic homogeneity down to the lower limit of resolution of the MFM (about 100 nm).

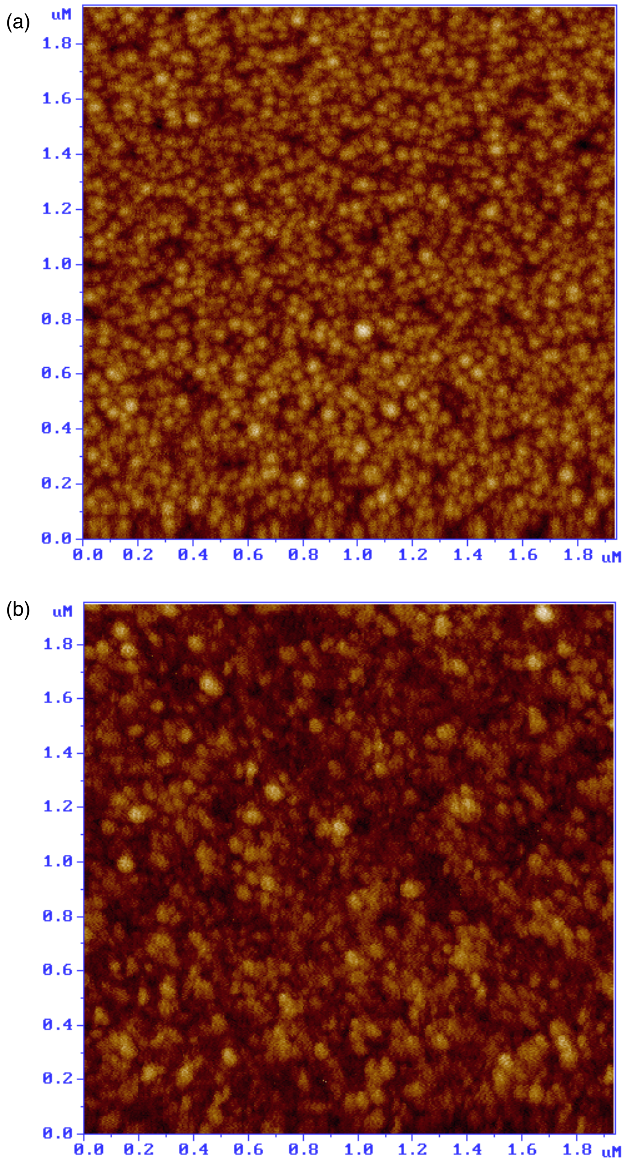


**Figure 2.** AFM micrographs of the surface morphology of ($a$) a 150 nm thick $Gd_{10}Tb_6Fe_{80}Co_4$ film prepared on a 140 nm thick Cr underlayer on an Si wafer and ($b$) a 140 nm thick single-layer Cr film deposited on an Si wafer.

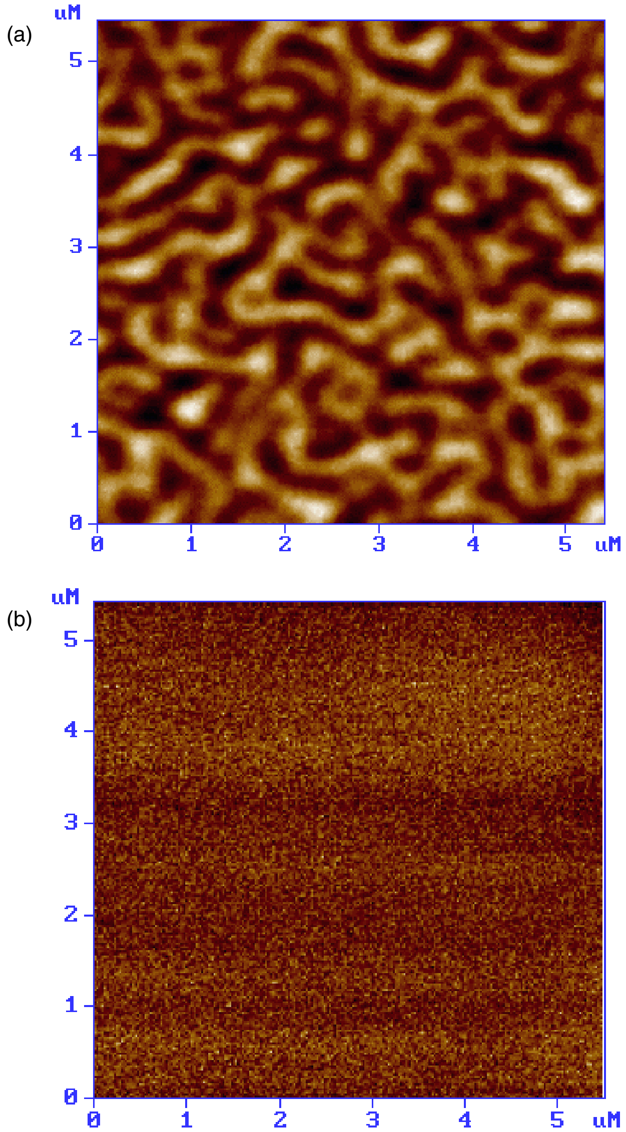


**Figure 3.** MFM micrographs showing the domain structure of a 150 nm thick $Gd_{10}Tb_6Fe_{80}Co_4$ film prepared on a 140 nm thick Cr underlayer on an Si wafer ($a$) unmagnetized and ($b$) magnetized.

SQUID magnetometer measurements of the magnetic properties of the $Gd_{10}Tb_6Fe_{80}Co_4$ films with Cr underlayers deposited on an Si wafer were also carried out, up to a maximum applied field of 10 kOe. Figure 4 shows a hysteresis loop measured at room temperature in the direction perpendicular to the film. It has a shape close to rectangular and indicates the film has an intrinsic coercivity of about 2.7 kOe and a remanent magnetization of about 265 emu $cm^{-3}$ (3.3 kG). The GdTbFeCo films deposited directly on Si were found to have inferior magnetic properties to those deposited on the Cr underlayer, particularly in terms of coercivity (<1.5 kOe).

The surface topology and magnetic characteristics of the magnetized grooved microstructures with periodicities of 1.5 and 3 $\mu$m coated with a 150 nm thick GdTbFeCo film on a 140 nm thick Cr underlayer were also investigated with AFM and MFM imaging. Figure 5 shows typical AFM topography and MFM phase images of the 3 $\mu$m period grooved microstructure obtained by scanning ($a$) the surface for the AFM image and ($b$) 100 nm above the top surface of the magnetized grooved microstructure for the MFM image. The AFM scan shows uniform periodic signals and indicates that the side walls are reasonably perpendicular with some rounding due to instrumental effects of the AFM. A statistical analysis indicates a surface roughness of about 2 nm (rms). The MFM images indicate excellent magnetic homogeneity, with no evidence of the domain structure of figure 3($a$). The variation of the $y$ (vertical) component of the magnetic field (to which the MFM is sensitive) with distance $x$ is approximately sinusoidal (figure 5($b$)), even at a height of only 100 nm (about $0.2 \times a/2\pi$) above the top surface. The observed sinusoidal dependence at distances very close to the surface is attributed to some rounding of the top edges of the groove walls during the fabrication process, which significantly decreases the

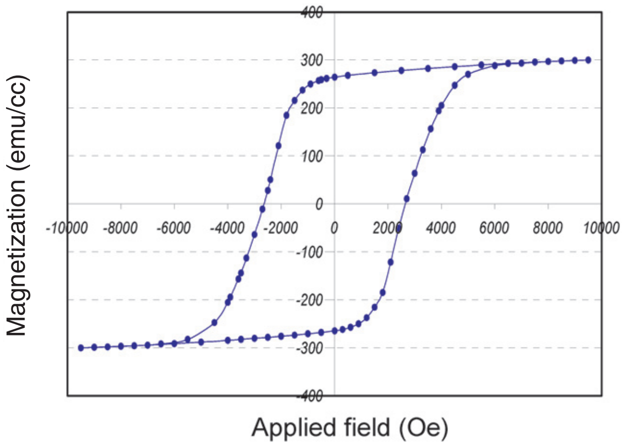


**Figure 4.** Hysteresis loop measured by SQUID magnetometry at room temperature in the perpendicular direction for a 150 nm thick $Gd_{10}Tb_6Fe_{80}Co_4$ film deposited on a 140 nm thick Cr underlayer on an Si wafer.

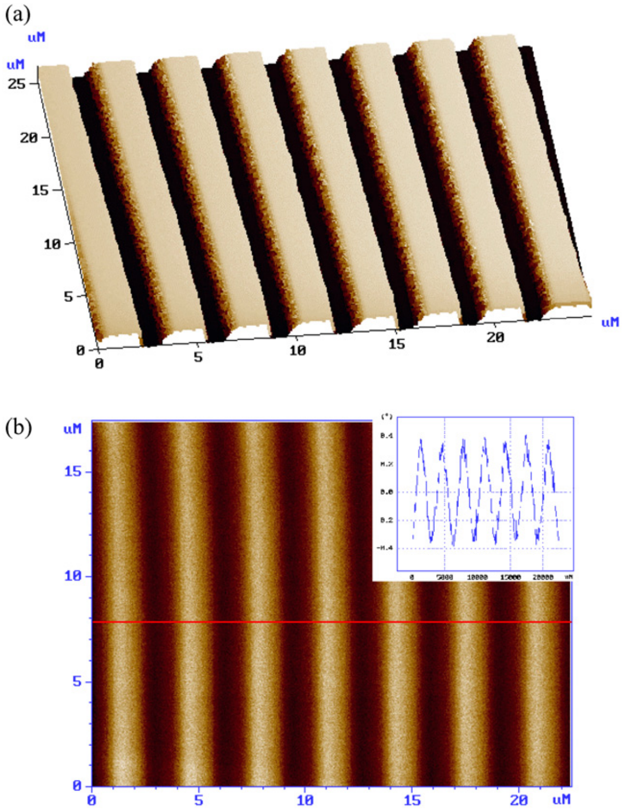


**Figure 5.** Micrographs of a perpendicularly magnetized grooved microstructure fabricated with a 150 nm thick $Gd_{10}Tb_6Fe_{80}Co_4$ film on a 140 nm thick Cr underlayer on a silicon grating structure with a period of 3 $\mu$m. (*a*) AFM scan and (*b*) MFM scan. In (*b*) the grooves are represented by the light regions and the inset shows a cross-section of the signal along the indicated horizontal line.

contribution of higher order spatial harmonics in the magnetic potential [19].

The films deposited onto the grating structure for cold atom experiments were fabricated with a multilayer structure comprising three 140 nm thick layers of Cr alternating with three 150 nm thick layers of $Gd_{10}Tb_6Fe_{80}Co_4$. This gave

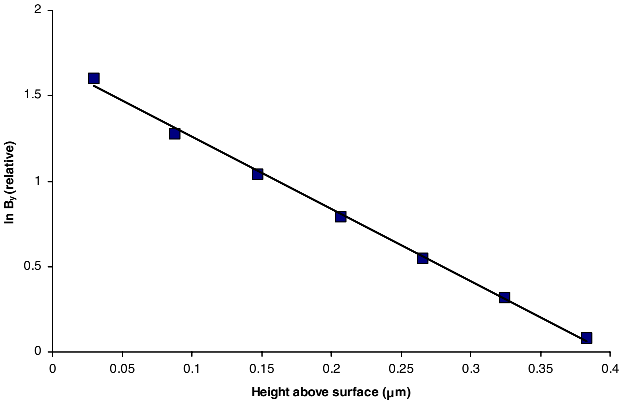


**Figure 6.** Plot of ln $B_y$ versus height above the surface for the $a = 1.5\,\mu$m perpendicularly magnetized grooved microstructure. The slope gives a decay length of 0.24 $\mu$m.

superior magnetic characteristics to films that had a single 450 nm thick layer of GdTbFeCo. Without the Cr mid-layers present the remanent magnetization and coercivity were found to deteriorate at thicknesses larger than about 200 nm, probably due to the magnetic anisotropy direction being less well defined; but by using the multilayer structure the overall thickness of the film could be built up beyond the thickness of 1 $\mu$m while still preserving good magnetic properties.

A strong indicator of how the grooved microstructures work as magnetic mirrors is the dependence of the magnetic field on height above the surface of the structure. The dependence on height $y$ above the 1.5 $\mu$m period grooved microstructure of the $y$-component of the magnetic field was tested by making a series of MFM scans with the magnetic tip at different heights ranging from 100 to 1500 nm above the top of the microstructure. From the MFM data it is possible to plot the dependence of $B_y$ on height $y$ (figure 6). The values of $B_y$ in figure 6, which are relative values determined from the amplitude of the MFM phase signal, indicate that the amplitude of $B_y$ decreases exponentially with height above the surface. The magnitude of the magnetic field is expected to decay with the same dependence. The slope yields a decay length of $(0.24 \pm 0.02)\,\mu$m, which is in agreement with $a/2\pi = 0.24\,\mu$m given by theory [2], with most of the uncertainty arising from the calibration of the vertical position of the MFM tip.

The MFM measurements do not give absolute values of the magnetic field above the surface, but we can use the value of the magnetization from the SQUID measurements to estimate how we expect the atom optical elements based on the multilayer GdTbFeCo film to perform. From equation (2), the magnitude of the magnetic field at the surface of the structure, using $a = 1.5\,\mu$m, $b = 0.45\,\mu$m and $M = 265$ emu cm$^{-3}$, is about 900 gauss. Given that a $^{87}$Rb atom in the $F = 2$, $m = 2$ ground state dropped from a height of 10 mm will be reflected by a field of 16 gauss, the reflection should occur about one micron above the surface, well above any surface effects and effects from the higher order terms in equation (1).

If the film is used on the surface of an atom chip, then, for example, a two-dimensional quadrupole magnetic trap is produced at a height of 25 $\mu$m above an edge of the film in the $x$ direction by applying a bias magnetic field of 10 gauss in the $z$ direction. If an additional field of 1 gauss is applied in the $x$ direction to suppress spin-flips, then the trap would have a radial trapping frequency of 5.4 kHz for ground state $F = 2$, $m = 2$ $^{87}$Rb atoms.

## 4. Conclusions

We have fabricated magnetic microstructures that show considerable promise as atom optical devices by depositing $Gd_{10}Tb_6Fe_{80}Co_4$ magneto-optical film with perpendicular magnetic anisotropy on grooved silicon microstructures with periodicities of 1.5 and 3 $\mu$m. When the magneto-optical material was deposited onto a Cr underlayer the magnetic characteristics of the films were found to be significantly improved, along with their surface topology and density. A single layer of the magneto-optical film deposited on a Cr underlayer was measured at room temperature in the direction perpendicular to the film to have an intrinsic coercivity of 2.7 kOe and a remanent magnetization of 265 emu cm$^{-3}$ (3.3 kG). The periodically grooved microstructures coated with GdTbFeCo films exhibit reasonably perpendicular side-walls and uniform periodic modulation in AFM and MFM scans. Optimum magnetic characteristics were found for multilayer structures of GdTbFeCo alternating with Cr. The amplitude of the component of magnetic field in the direction perpendicular to the grooved microstructure surface was found to decrease exponentially with height above the surface with a decay constant consistent with the theoretical value given by the period of the microstructure. Such perpendicularly magnetized grooved microstructures coated with GdTbFeCo films should be well suited for atom optical applications.

## Acknowledgments

This work is funded by a Systemic Infrastructure Initiative (SII) grant from the Department of Education, Science and Training (DEST), the ARC Centre of Excellence for Quantum-Atom Optics and a Swinburne University Strategic Initiative grant. We thank Dr T Hicks and Mr D Robinson for their help with the SQUID analysis at Monash University, Australia, and W A Challener and J Sexton of Imation Corp., USA for supplying the early GdTbFeCo samples.

## References


[1] Metcalf H J and van der Straten P 1999 *Laser Cooling and Trapping* (Heidelberg: Springer)
[2] Opat G I, Wark S J and Cimmino A 1992 *Appl. Phys.* B **54** 396
[3] Hinds E A and Hughes I G 1999 *J. Phys. D: Appl. Phys.* **32** R119
[4] Sidorov A I, Lau D C, Opat G I, McLean R J, Rowlands W J and Hannaford P 1998 *Laser Phys.* **8** 642
[5] Davis T J 2001 *Eur. Phys. J.* D **14** 111
[6] Opat G I, Nic Chormaic S, Cantwell B P and Richmond J A 1999 *J. Opt. B: Quantum Semiclass. Opt.* **1** 415
[7] Sinclair C D J, Retter J A, Curtis E A, Hall B V, Llorente Garcia I, Eriksson S, Sauer B E and Hinds E A 2005 *Preprint* physics/0502073
[8] Myatt C J, Newbury N R, Guist R W, Luitzenhiser S and Wieman C E 1996 *Opt. Lett* **21** 290
[9] Richmond J A, Cantwell B P, Nic Chormaic S, Lau D C, Akulshin A M and Opat G I 2002 *Phys. Rev.* A **65** 33422
[10] Roach T M, Abele H, Boshier M G, Grossman H H, Zetie K P and Hinds E A 1995 *Phys. Rev. Lett.* **75** 629
[11] Hughes I G, Barton P A, Roach T M, Boshier M G and Hinds E A 1997 *J. Phys. B: At. Mol. Opt. Phys.* **30** 647
[12] Hughes I G, Barton P A, Roach T M and Hinds E A 1997 *J. Phys. B: At. Mol. Opt. Phys.* **30** 2119
[13] Saba C V, Barton P A, Boshier M G, Hughes I G, Rosenbusch P, Sauer B E and Hinds E A 1999 *Phys. Rev. Lett.* **82** 468
[14] Sidorov A I, McLean R J, Rowlands W J, Lau D C, Murphy J E, Walkiewicz M, Opat G I and Hannaford P 1996 *Quantum Semiclass. Opt.* **8** 713
[15] Meschede D, Bloch I, Goepfert A, Haubrich D, Kreis M, Lison F, Schutze R and Wynands R 1997 Atom Optics *Proc. SPIE* **2995** 191
[16] Sidorov A I, Lau D C, Opat G I, McLean R J, Rowlands W J and Hannaford P 1997 *Proc. 13th Int. Conf. on Laser Spectroscopy (Hangzhou, China, 1997)* (Singapore: World Scientific) p 252
[17] Lau D C, McLean R J, Sidorov A I, Gough D S, Koperski J, Rowlands W J, Sexton B A, Opat G I and Hannaford P 1999 *J. Opt. B: Quantum Semiclass. Opt* **1** 371
[18] Sidorov A I, McLean R J, Sexton B A, Gough D S, Davis T J, Akulshin A M, Opat G I and Hannaford P 2001 *C. R. Acad. Sci. Ser.* IV **2** 565
[19] Sidorov A I, McLean R J, Scharnberg F, Gough D S, Davis T J, Sexton B A, Opat G I and Hannaford P 2002 *Acta Phys. Pol.* B **33** 2137
[20] Tsunashima S 2001 *J. Phys. D: Appl. Phys* **34** R87
[21] Eriksson S, Ramirez-Martinez F, Curtis E A, Sauer B E, Nutter P W, Hill E W and Hinds E A 2004 *Appl. Phys.* B **79** 811
[22] Gough D S, McLean R J, Sidorov A I, Lau D C, Koperski J, Rowlands W J, Sexton B A, Hannaford P and Opat G I 1999 *Proc. 14th Int. Conf. on Laser Spectroscopy (Innsbruck, Austria)* (Singapore: World Scientific) p 380
[23] Folman R, Kruger P, Schmiedmayer J, Denschlag J and Henkel C 2002 *Adv. At. Mol. Opt. Phys.* **48** 263
[24] Hall B V, Whitlock S, Scharnberg F, Wang J Y, Dalton B J, McLean R J, Kieu T D, Hannaford P and Sidorov A I 2004 *XIX Int. Conf. on Atomic Physics (Rio de Janeiro, Brazil, 2004)* Book of Abstracts, p 87
[25] Kryder M H 1993 *Annu. Rev. Mater. Sci* **23** 411
[26] Challener W A 1997 Private communication