DIRECT LASER INTERFERENCE PATTERNING OF MAGNETIC THIN FILMS

by

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University of Nebraska GRADUATE COLLEGE

DIRECT LASER INTERFERENCE PATTERNING OF MAGNETIC THIN FILMS

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University of Nebraska, 2004

Advisor: Roger D. Kirby

Recently, patterned magnetic thin films have attracted much attention for a variety of applications such as high density magnetic recording, magnetoresistive sensing, and magnetic random access memories. In the case of magnetic recording, one scheme calls for the films to be patterned into single domain "dots", where every dot represents a thermally stable bit.

In this thesis, we extended a technique called direct laser interference patterning (DLIP), originally developed by Polushkin and co-workers, to pattern and locally modify the materials properties of magnetic thin films. In this technique, a high-intensity Nd:YAG pulse laser beam was split into two, three, or four beams, which are then recombined to interfere on a sample surface. The interference intensity maxima can modify the local materials properties of the film through local "annealing" or, more drastically, by ablation.

We carried out some preliminary investigations of the DLIP process in several films including co-sputtered Co-C, amorphous Dy/Co:SiO_2 multilayers, and Co/SiO_2 multilayers in order to refine our techniques. We successfully produced regular arrays of lines, dots, or antidots formed by ablation of the thin film. The preliminary studies also showed that, in the regime of more modest pulse energies, it is possible to modify the magnetic properties of the films without noticeably changing the film topography. We

then prepared perpendicular magnetic anisotropy Co/Pt multilayers with a SiO_x passivation layer and applied DLIP at fairly modest intensities to pattern the film. We then studied the structural and magnetic changes that occurred in some detail. X-ray diffraction scans showed the Co/Pt:SiO_x multilayer films to be nanocrystalline before and after patterning. Atomic force microscopy images showed no evidence for topographic changes of the Co/Pt:SiO_x during patterning. In contrast, magnetic force microscopy showed regular periodic dot arrays, indicating that the local magnetic properties were significantly affected by the patterning process. Alternating-gradient-force magnetometry and magneto-optic measurements also showed that the magnetic properties were markedly changed by the DLIP process. Our results offer strong evidence that local heating causes the moments to change from perpendicular to in-plane, with the consequent formation of an "anisotropy lattice": dots of in-plane magnetization within a matrix of perpendicular magnetization.

We also carried out some optical interference calculations to predict the light intensity distributions for two, three, and four interfering beams of light. We found that the patterns could be controlled by varying the angles of incidence, the polarizations of the beams, and the wavelength and intensity of the beams, and that a wide variety of patterns are possible. The predicted patterns were in quite good agreement with those observed experimentally.

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List of figures

Contents

Chapter 1. Introduction

The length scale of magnetic information storage technology is rapidly approaching the ten nanometer range, storage densities are projected to increase to a terabit per square inch in the next decade and most of the recent explosive growth in magnetic data storage has been due to new material discoveries and fabrication techniques and better understanding of the magnetic and electronic properties of complex magnetic thin film systems. These systems are used in a large variety of applications including magnetic media, magnetic recording heads, magnetic random access memory, sensors, and actuators [1.1, 1.2].

Development of many new magnetic materials with exciting and novel properties is in progress in laboratories around the world. A detailed knowledge of the physical and magnetic microstructure is important if the properties of modern magnetic materials are to be understood and subsequently improved. Many important properties of materials displaying an ordered magnetic phase depend on the magnetic domain configuration present within the material. Many such desirable magnetic properties are induced by a particular film growth or fabrication procedure, rather than being intrinsic to the material itself. Thus optimization of the macroscopic magnetic properties is only likely to be achieved if the magnetic nanostructure can be determined and its dependence on the physical nanostructure investigated.

Study of regularly-shaped magnetic thin film elements whose in plane dimensions vary in sub-micron range, as compared to larger structures, allows the influence of

particle shape and size to be studied more thoroughly in that surface effects are more important in smaller structures.

The term "ordered patterned media" is used to refer to thin films which consist of arrays of discrete elements, each of which can store one bit of data. In the simplest scheme, the magnetic elements could have only a single axis of magnetization. The direction of magnetization is interpreted as a binary 1 or 0. Ideally, the storage density is then equal to the surface density of the elements. In many patterned media, each discrete element is exchangely isolated from other elements, but inside each element polycrystalline grains are strongly exchange-coupled and behave collectively like a larger single magnetic grain. The problem with patterned media is that there have been no cheap and mass-production-compatible manufacturing methods capable of making them, as their surface density implies that both the linear bit density (bits per inch) and the track density (tracks per inch) must be in the deep sub-micrometer range. Conventional lithographic methods either are too time-consuming or do not handle the small structure sizes needed [1.3, 1.4].

For a successful application of the concept of ordered patterned media the development of a suitable patterning technique is one of the crucial items. The requirement of patterning large areas with regularly spaced uniform dots with small spacing puts strong demands on the patterning technology. However, our goal in this work was to prepare patterned magnetic thin films and study their relevant magnetic properties rather than to design a patterning technology for the manufacture of patterned magnetic thin films.

In the last decade, several lithography techniques were developed to fabricate regular-ordered patterned surfaces, including nanoimprint lithography [1.5], electron beam lithography and electroplating [1.6], laser interference lithography [1.7], synchrotron radiation based X-ray lithography [1.8] and scanning tunneling microscope lithography [1.9]. However, these techniques are time consuming and often need multi-step processes such as mask preparation, resist spinning, exposure, developing, etching and resist removal.

We have extended a direct laser interference patterning (DLIP) technique originally developed by Polushkin and co-workers [1.10].Using this technique, one can modify the topography and intrinsic material properties and create a regular patterned arrays. Specifically, this technique allows thin films to be patterned directly, without the need for an intermediary photoresist mask or hard mask. The purpose of this thesis work is to utilize the DLIP to pattern and locally change the topographic and/or magnetic properties of magnetic thin films and multilayers including Co/Pt:SiO, amorphous Dy/Co:SiO_2 and co-sputtered Co-C. Results on these films will be presented, and we will offer evidence that such patterns can form an “anisotropy lattice”, where “dots” of in plane magnetization are formed in a background matrix of perpendicular magnetization.

The DLIP technique is based on the pattern produced by two, three or four interfering laser beams of a given wavelength. The standing wave interference pattern produces alternating light and dark regions with a spacing determined by the wavelength and the angles at which the beams intersect. For a Nd:YAG laser operating at the second harmonic wavelength (532 nm), lines, dots down to 300 nanometers in diameter can be

fabricated, With a single pulse exposure, many patterns such as lines, elongated lines, dots, and anti-dots, can be formed and fabricated.

In Chapter 2 of the thesis details of film preparation, including the sputtering process and the mass calibration is introduced. Then the magnetic and structural measurement methods are briefly discussed and described. These include: X-ray diffraction (XRD) to detect the structure changes, Atomic Force Microscopy (AFM) to measure the topographic changes, and Magnetic Force Microscopy (MFM)to study magnetic domains. In addition, magneto-optic Kerr effect (MOKE) and an alternating gradient field magnetometer (AGFM) were used for magnetic property measurements of the various films at room temperature before and after DLIP. In Chapter 3, the experimental details and principles of the direct laser interference patterning (DLIP) technique are described. In Chapter 4, the classical theory of electromagnetic radiation is used to derive expressions to calculate interference intensity distributions for two to four beams of linearly polarized light. These expressions are evaluated numerically using the symbolic algebra program, "Maple" for several different situations, and graphical simulation results are presented. In Chapter 5, in addition to a brief discussion on the laser-matter interaction, the properties of Co-C, amorphous Dy/Co:SiO_2, and Co/SiO_2 magnetic thin films, patterned and modified by DLIP, are presented. In Chapter 6, the film characterization (XRD), magnetic (AGFM, MFM) and magneto-optic properties (MOKE) measurements and the magnetic modifications (AFM/MFM) made by DLIP, on Co/Pt:SiO_x multilayer thin films are presented. The results are given and discussed in more detail. Finally, in Chapter 7, a summary of the results and the conclusions is given.

Chapter 2. Thin Film Preparation and Characterization

Co/Pt: SiO_x, amorphous Dy/Co: SiO_2, Co/SiO_2, and Co-C multilayer thin films were prepared in a three-gun magnetron sputtering system. In this chapter, the thin film preparation process, structural and magnetic characterization methods are described.

2.1. Thin film preparation

For all prepared films Si(100) was used as substrate. Before the substrates were placed into the sputtering chamber they were ultrasonically cleaned in acetone to remove dust and grease. The films were deposited in a homemade three-gun (1-RF and 2-DC) magnetron sputtering (Dale) system with a computer-controlled, water-cooled rotating substrate holder. To minimize contamination, the chamber was evacuated to a good vacuum by a diffusion pump and a base pressure of $5x10^{-7}$ torr was reached prior to sputtering. Sputtering was carried out at 5 mtorr of pressure in argon environment. The multilayer films were prepared by alternately positioning the substrates above different targets for different time durations. The sputtering rates were adjusted and controlled by varying the power to the sputtering guns. The deposition rate of a particular material was calibrated by measuring the mass of the material deposited for various sputtering powers and a fixed period of time. After calibration, the layer thickness of each component of the multilayer film was controlled by the time that the substrate remained above the gun. Total film thickness and the sequential depositions of multilayer components were controlled by a standard computer program. 99.99% pure Co, Pt, Dy and C target

materials were used as sputtering sources. The DC sputtering guns were used for multilayer depositions of Co, Pt, Dy and C target materials, and the RF gun was used for SiO_x or SiO_2 as an insulating overcoat material to passivate the film surfaces after removal from the sputtering chamber.

Sputtering rate calibrations for the materials used in the sputtering processes were done as follows: For each target, usually four 2 x 2 cm aluminum foils were cut and ultrasonically cleaned in acetone or ethyl alcohol, and then their weights were measured twice using a very sensitive digital balance and averaged. The nominal accuracy of the balance was 10^{-3} mg. The foils were mounted in the sputtering chamber. Depending on the material to be sputtered and the particular sputtering gun, gun powers and periods of time were increased or decreased in stepwise manner and recorded. After sputtering, the foils were again weighed twice and averaged. The change in weight due to sputtering determines the amount of mass deposited in the aluminum foil at certain power and period of time. Using the expression of the rate, R, for a certain power,

$$R = \Delta M/(\rho A t) \qquad (2.1)$$

was calculated for a particular material (Co, Pt, Dy, C, SiO and SiO_2). In the expression ΔM is the weight difference, ρ is the mass density, A is the sputtered area and t is the period of time. Finally, from the plot of the sputtering rate versus power, which is a straight line for most of the materials, the desired sputtering rate could be chosen.

2.2 Thin film structural characterization

2.2.1 X-ray diffraction

The structures of the films were investigated before and after direct laser interference patterning (DLIP) processes using a Rigaku X-ray diffractometer with a Cu source. The 2θ X-ray diffraction (XRD) patterns were used to analyze the crystal structure. The 2θ XRD profile is divided into two regions: low-angle (<15°) and high-angle (> 15°). Diffraction due to the chemical modulation of the layers appears in the low-angle XRD region and is used to determine the bilayer thickness. The position of the peaks are determined by [2.1]

$$\sin^2\theta = \left(\frac{n\lambda}{2\Lambda}\right)^2 + 2\delta_s, \qquad (2.2)$$

where λ is the X-ray wavelength, n is the order of the reflection, Λ is the bilayer thickness of the multilayer, and δ_s is the correction of the refraction index due to the small incident angle. The typical value for δ_s is ~3×10^{-5} which only leads to significant deviations from Bragg's law when 2θ < 3° for Cu radiation. Thus, it was ignored in this work. As an example, Fig. 2.1 shows a simulation of a low-angle 2θ XRD pattern for a perfect multilayer of [Co(4Å)/Pt(10Å)]x11 thin film [2.2].