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Magneto-optical visualisation for high-resolution forensic data recovery using advanced thin film nano-materials

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Abstract

We develop and characterise new high-performance nano-engineered magneto-optic materials for use in laser-microscopy-based magnetic field visualisers featuring high sensitivity and resolution, low cost and small size. This type of visualisers will make it possible for forensic experts to recover erased data previously stored in high- and ultrahigh-density magnetic disks and hard disk drives.

Introduction

The magnetic media (floppy disks, hard drives, reel-to-reel tapes, eight-tracks, and others) are commonly used as the primary storage device for a wide range of applications, including desktop, mobile, and server systems. All of these are using magnetic fields to store and read out data as they are very sensitive to magnetic fields. Currently, Magnetic Force Microscopy (MFM) and magnetic force Scanning Tunnelling Microscopy (STM) are the most commonly used techniques for imaging the magnetisation patterns with high resolution [1-5]. However, typical users cannot benefit from these existing techniques for the recovery of data stored in ultrahigh-density magnetic media due to poor resolution and bad visibility. Also, conventional data recovery systems are quite difficult to handle, bulky, expensive, and require a long sample preparation time. The visualization of magnetic features within a solid medium based on using magneto-optical effects is of relevance in the field of digital forensics. Rare-earth-doped iron-garnet thin films are very promising magneto-optic (MO) indicator films that can visualise the magnetic leakage fields generated by magnetised objects in situations requiring non-destructive evaluation, can measure magnetic flux distributions in superconductors, or image magnetic patterns on audio tapes and digital disks [6-8].

Magneto-optical investigation techniques are critically dependent not only on the optical system and the geometry (MO thin film thickness) but also on the material parameters (magnetic anisotropy, Faraday rotation, domain size). Bismuth-substituted iron garnets (Bi:IG) are a very attractive class of MO materials suitable for various magneto-optical applications such as MO visualization. This is due to the extraordinary high Faraday rotation per unit thickness and very low optical absorption in the infrared and (except the blue-green region) in the visible spectral ranges. Bi-substituted garnet films can possess strong uniaxial magnetic anisotropy and show the magnetic domain patterns which can be designed to interact with the magnetic bit patterns recorded on the storage media. Thick Bi:IG fabricated using pulsed laser deposition (PLD) techniques as well as multilayer structures comprising MO thin films compact in between dielectric mirrors have been proposed for MO visualization applications, where the compact multilayer films enhance the Faraday rotation and the saturation field. Also several optimised magnetic photonic crystals (MPC) have been designed and reported for various applications including magnetic field visualisation using reflection- and transmission-mode polarising microscopes. The magnetic layers inside the photonic crystal structure allow switching of their optical properties even with relatively-small external magnetic fields [9-11]. We have established several novel MO garnet compositions by fabricating $(Bi,Dy)_3(Fe,Ga)_5O_{12}$: Bi_2O_3 garnet-oxide composites using RF magnetron sputtering technique followed by conventional oven annealing in air atmosphere. The optical and MO properties of high performing garnet composites have been studied and record-high MO quality in the visible spectral range as well as strong uniaxial anisotropy have been reported [12]. These materials are suitable for use in high-contrast magnetic field visualisers due to their superior magnetic and MO properties. In particular, these thin-film iron garnet materials exhibit very strong Faraday rotation and also an adequate transmission at UV wavelengths (in very thin films) leading to both high imaging contrast and potentially ultra-high resolution.

Based on the combination of existing expertise in the areas of material development, nanostructure design and imaging available at ESRI, ECU, new methods of MO imaging are explored in this paper, using high-quality magnetic nanostructures for the development of magnetic field visualisers capable of the recovery of data stored in various high-density magnetic recording media.

MO visualisation using garnet thin films

The basic principle of MO imaging and visualisation technique using garnet thin films is illustrated in Fig. 1, where polarised input light is used in conjunction with a nano-engineered magnetic field imager. If UV or blue-range visible light sources are used, sub-micron spatial resolutions, capable of magnetic hard drive data imaging, can be attained. The MO imager film is placed very close to the surface of the disk being imaged (this “flying distance” needs to be of the order of the bit size, ~100 nm), and this is technically feasible, especially because the nano-structuring of our ultra-thin multilayers can reduce the switching magnetic fields to below 50-100 Oe. The magnetic structures of the data recorded on the media are imprinted into the MO thin films and are memorised by the films, allowing post-processing of the captured data distributions, as well as transmission-mode imaging. Moreover, due to the advantage of the low Curie temperature (T_C) of the magneto-optical materials (~180 °C), the coercive force reduces significantly by heating the visualiser to above T_C just before placing them in close proximity with the disk surface. After cooling the thin film, the data is memorised by the thin-film visualizer for later imaging and processing.

The data bits recorded onto the magnetic medium under investigation generate a stray magnetic field that magnetises the MO imager’s thin film layer. The latter rotates the polarisation of the input light by an angle that depends on the data recorded. An output analyser, set near the extinction condition with respect to the input light polarisation, generates a magneto-optic image of the data tracks.

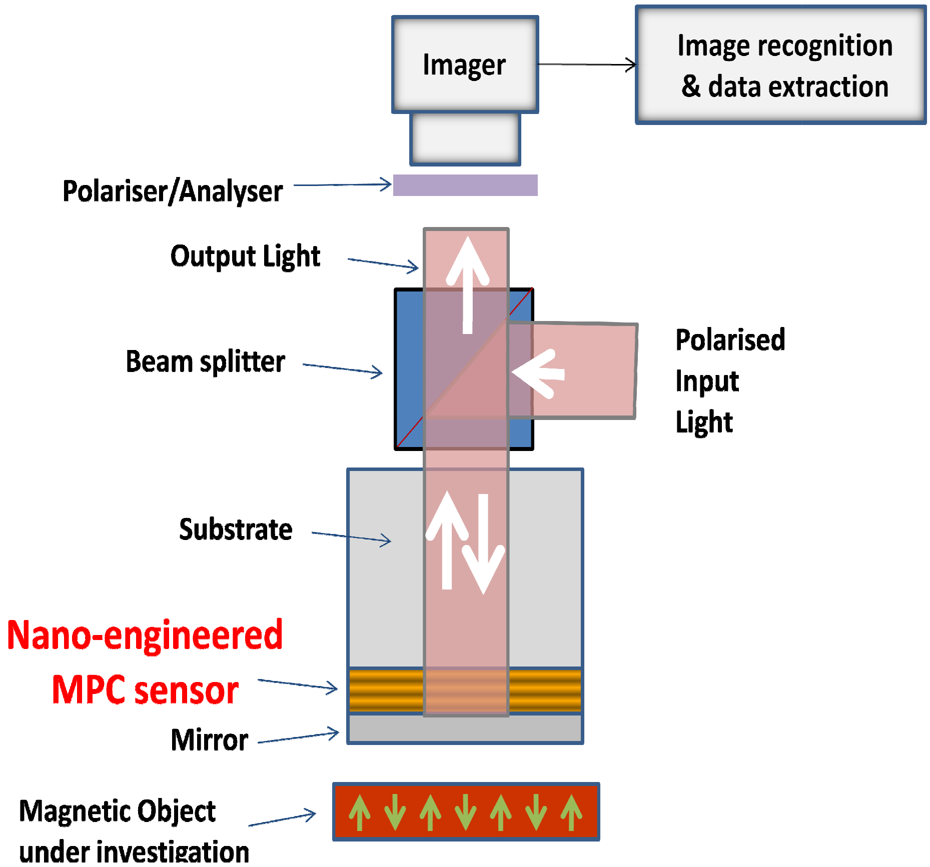

Fig. 1. Schematic diagram of Magnetic field visualiser demonstrator for hard drive data recovery.

Results and discussion

Thin film materials preparation and characterization

Bi-substituted iron garnet films were prepared by fabricating $(BiDy)_3(FeGa)_5O_{12}$ ferrimagnetic garnet films and also $(BiDy)_3(FeGa)_5O_{12}$: Bi_2O_3 garnet-oxide composites on glass (Corning 1737) and monocrystalline GGG (111)-oriented substrates by RF magnetron sputtering using low-pressure (1-2 mTorr) argon plasma. The imager films were annealed in a conventional temperature- and ramp-controlled oven system using optimised annealing regimes which were found to be extremely composition-dependent. Our MO garnet films possess excellent optical and MO properties, making them very attractive and promising for a large range of optical, photonics-related and MO applications. We experienced the lowest visible-range optical absorption coefficients through our new composite materials which were comparable to these typically achievable so far only in monocrystalline garnet layers fabricated using liquid-phase epitaxy [13]. The highest values of the specific Faraday rotation in our materials were more than 10 deg/μm at 532 nm and up to about 2.6 deg/μm at 635 nm in films with the lowest-achieved absorption coefficients of between 6000-7000 cm^{-1} at 532 nm and 1100- 1300 cm^{-1} at 635 nm. These properties, together with the presence of domain structure make our films suitable for MO imaging applications.

Magnetic domain patterns typically observed in our films (obtained in a demagnetized state, immediately after the annealing and cooling processes) using a transmission-mode polarizing microscope are shown in Fig. 2. The completely microcrack-free garnet films possessed high-contrast domain patterns, excellent crystallinity and very small grain (crystallite) size (of about 40-50 nm) as well as very small (submicron-scale) magnetic domain size. The magneto-optic imaging mechanism is critically dependent on the domain size of the garnet thin films, since each magnetic domain is essentially used as a “bit” in the digital-type compound images obtainable after being brought into the close proximity of the magnetised object under study.

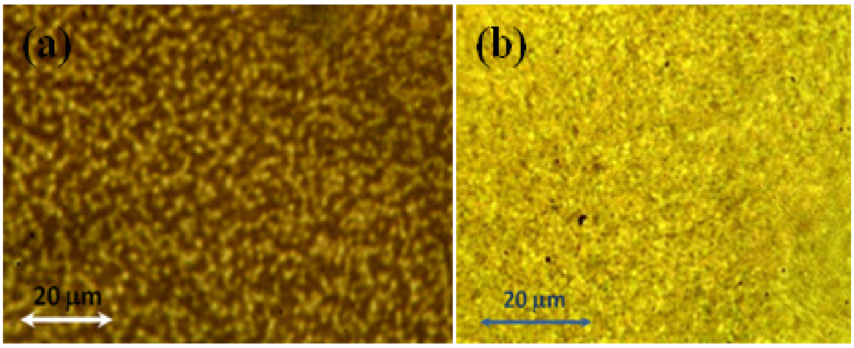

Fig. 2. Magnetic domain patterns observed using a transmission-mode polarizing microscope in two different demagnetised garnet-oxide composite films sputtered onto gadolinium gallium garnet (GGG) substrates.

The thin-film substrate types and also the MO material composition used have a great influence on the magnetic hysteresis (nearly square loop observed) loop properties of our films, which opens the opportunity to engineer these materials in terms of the required coercive force and switching field properties [14]. Our sputtered MO garnet materials possess a combination of the optical and magnetic properties suitable for use in contact-less non-destructive high-density magnetic media imagers. Fig. 3 shows the imaging results of the magnetic media data patterns achieved using a brief mechanical contact of our films with these media. Visible-light polarisation microscopy was used to generate images (a, b) and UV (365 nm) polarisation microscopy was used to generate images (c, d). Using short-wavelength (UV) illumination, we can achieve imaging resolutions suitable for working with high-density storage media whilst staying within the Rayleigh limit.

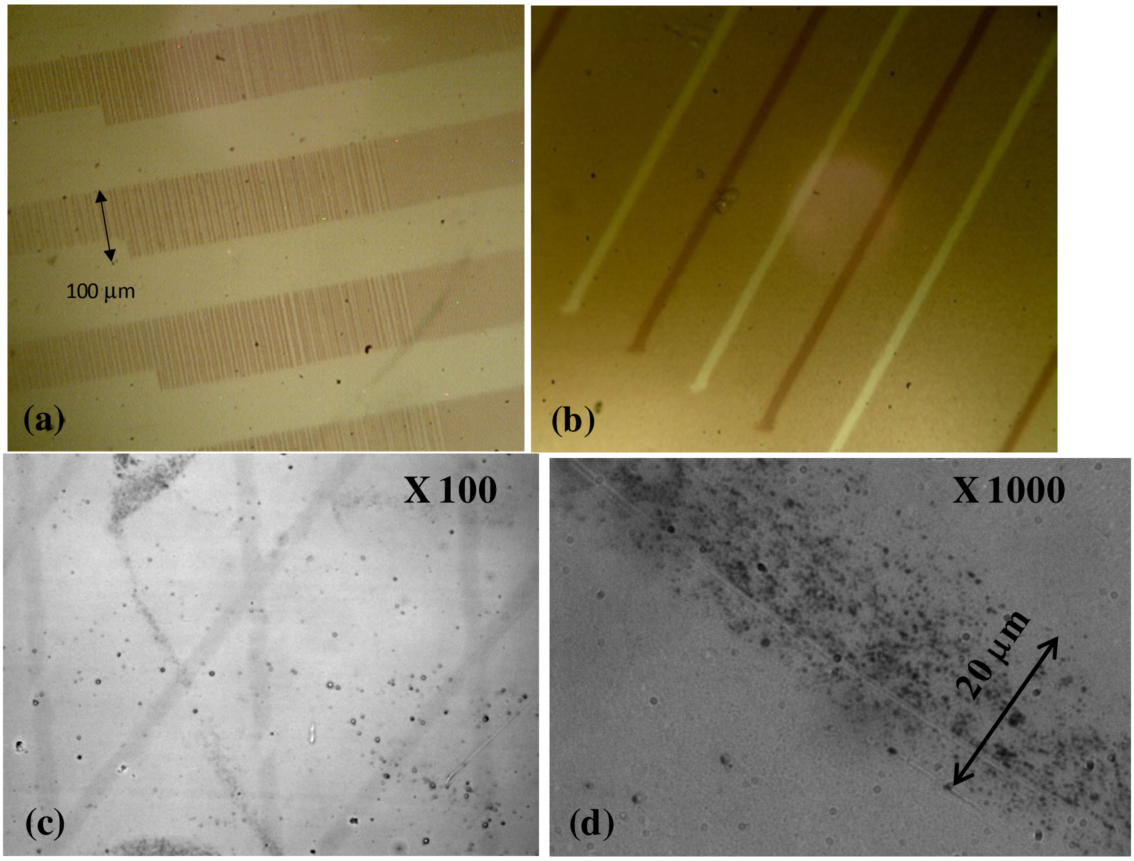

Fig. 3. Transmission-mode polarising microscope images of (a) data tracks recorded on a 3.5'' (1.44 MB) HD floppy disk; (b) magnetic patterns of a credit card obtained by bringing the media surface momentarily into a close proximity of a MO garnet material layer; (c) UV (365 nm) transmission-mode polarisation microscopy image of a 500 nm-thick MO garnet film with several imprints of credit card data stripes recorded magnetically inside the film layer, magnification X100. The stripes' width is about 20 microns; (d) X1000 image of a small area of sample shown in (c), demonstrating the possibility of achieving sub-micron-scale imaging resolution. The images (c) and (d) generated using a ECU-made MO film are courtesy of CRAIC Technologies Inc., USA.

CONCLUSION

We have demonstrated the suitability of our sputter-deposited high-performance magneto-optic films for use in imaging of the data tracks stored in several magnetic media and proposed an extension of the standard MO imaging techniques for forensic data recovery applications using UV polarisation microscopy and nano-engineered magnetic imagers. This will open up the possibilities of capturing and storing the data recorded on high-density magnetic storage media such as hard disk drives, which is expected to potentially change the industry practices used in forensic and data security areas.

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