E 2 Magneto-optical Discs

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1 Introduction

Optical data storage devices are available at present in various types. In the well known audio compact disc CD and in the commonly used CD-ROM a binary information is stored in form of small pits which are embossed into the surface of a polymer disc during the fabrication process. The pits are arranged in tracks 1.6 μm apart and have a minimum length of 0.83 μm. A similar principle is applied in the present generation of digital versatile discs DVD where the minimal length of the pits is 0.40 μm and the track pitch is 0.74 μm. For the read out process a laser is focussed through the transparent substrate to the track where the pits cause intensity modulations of the reflected light during disc rotation.

Similar principles are applied in the WORM (write once read many) medium CD-R and in the rewritable CD-RW media as well as in the magneto optical (MO) discs [1-4]. The information is written in a thin layer on one surface of the disc by means of local heating by a laser pulse. In case of CD-R the radiation is absorbed by a dye layer which process leads to local variations of the reflectivity. In CD-RW discs changes of reflectivity are created by transitions between amorphous and crystalline states of the information layer. A reversible transition can be obtained by different pulse lengths and power levels.

2 Principle of magneto optical data storage

A thermomagnetic writing process is used in the MO media (figure 1). A magnetic layer which is homogeneously magnetized in one direction, is heated by the laser pulse to a sufficiently high temperature, where the coercivity H_c of the magnetic layer is smaller than a simultaneously applied bias field H_b. By this process a small domain is created the magnetization of which is opposite to the original magnetization direction. As a result small bubble domains with magnetization down are formed in a surrounding with magnetization up which can be attributed to the binary numbers 1 or 0.

For read out the magneto optical Kerr effect (MOKE) is applied. When polarized light is reflected from a sample with magnetization M perpendicular to the surface the polarization becomes elliptical with a small tilt (Kerr rotation) Θ_k and an ellipticity ε_k which are proportional to the magnetization (Polar Kerr effect). By means of a polarizer the Kerr rotation and the Kerr ellipticity can be transformed into an intensity modulation of the reflected light which corresponds to the binary information represented by the bubble domain structure.

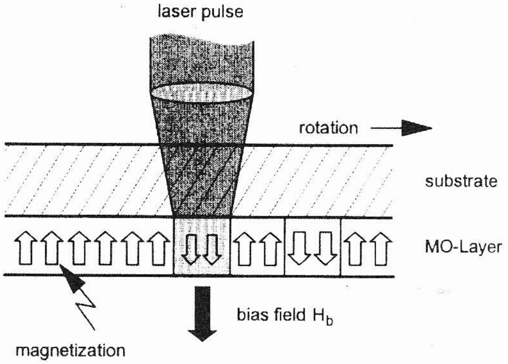


Fig. 1 Principle of magneto-optical recording [3]

The overwrite of a given information by new information can be performed by magnetic field modulation (MFM) when the bias field is appropriately switched from one direction to the other between sequential laser pulses. This method is applied in the well known MiniDisc (MD) which operates at a frequency of 44.1 kHz. For computer applications, however, the required high frequency is not compatible with the MFM technique. In the first step, therefore, the information is erased along the track by a continuous laser heating in presence of a constant bias field. In the next step new information is written by the thermomagnetic process and, finally, read out for verification. The overwrite process, therefore, requires at least two rotations of the disc which reduces the average access time. Attempts have been made to obtain a direct overwrite (DOW) by appropriate layer systems (see section 4).

A cross section of the magneto optical disc is shown in figure 2. A polycarbonate substrate 1.2 mm thick with grooves on one side is formed by injection molding. The pregrooved surface is then coated with the storage medium by sputter deposition. Finally a protective layer about 10 µm thick is prepared by spin coating of a lacquer. In order to obtain double capacity often two discs are glued together with the storage layers in the middle of the disc. The land and groove structure is necessary for focussing and tracking of the optical head during disc rotation. The magnetic information is written normally on the land areas of the medium. The track pitch in the present MiniDisc, for instance, is 1.6 µm and the width of the land area is 1.2 µm. The depth of the groove is approximately 100 nm. As the light is focussed through the substrate to the track, the diameter of the laser beam at the disc surface is of the order of 1 mm. Therefore small contaminations on the substrate surface, for instance dust, do normally not disturb the signal.

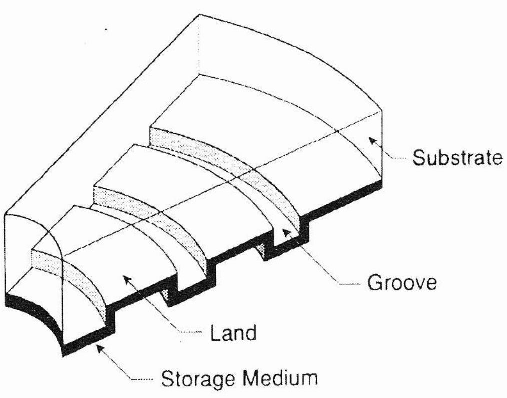


Fig. 2 Cross section of a magneto-optical disc [1]

An example of a storage medium is shown in more detail in figure 3 [2]. The essential part is a very thin magneto optical layer (thickness typically 25 nm) of TbFeCo, where the magnetic domains are formed. Because the rare earth Tb is very sensitive against corrosion and oxidation the MO layer is protected from both sides by layers of Si_3N_4 which prevent diffusion of water vapour from the polymer substrate or from the lacquer into the magneto optical layer. In addition the SiN layers act as antireflecting coatings and improve the read out signal. A further increase of the signal is achieved by an Al reflecting layer because the reflected beam can pass the MO layer twice.

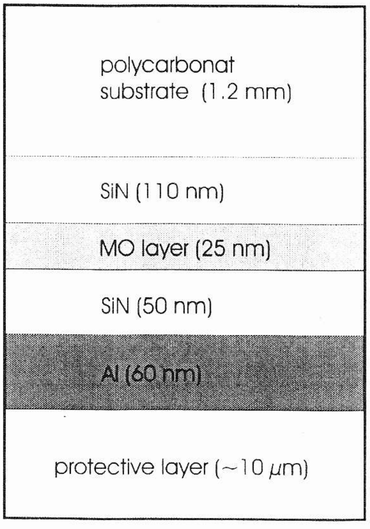


Fig. 3 Layer stack of a typical MO Disc [2]

3 Material properties

The polar Kerr effect used for the read out procedure is sensitive to the magnetization component perpendicular to the film plane. In order to obtain a complete perpendicular orientation a sufficiently high perpendicular anisotropy K_u is necessary. It must be larger than the shape anisotropy which is proportional to M_s^2:

$$K_u \geq (1/2)\, \mu_0\, M_s^2 \tag{1}$$

The condition can be fulfilled by amorphous films consisting of rare earth (RE) and transition metal (TM) components (see article of Gambino in [2]). A typical example is $Tb_{75}Fe_{25}$ where the Tb and the Fe elements can be partially substituted by other RE or TM atoms, for instance Gd, Dy... or Co, Ni..., respectively. Because the films have an antiferromagnetic coupling between the RE and the TM components, the net magnetization M_s can be small in spite of the fact, that the magnetizations of the RE and TM subnetworks are high. As the temperature dependencies of the two subnetwork magnetizations are different often a compensation temperature exists where the net magnetization is even zero (figure 4). At this compensation temperature T_{comp} the coercivity of the material becomes infinite because an external field can not turn the magnetization into any given direction. This is important for the stability of the domains. At a high temperature near the Curie temperature T_C the coercivity is sufficiently small to form a domain by the external bias field H_b. During cooling to room temperature the coercivity increases rapidly and, as a consequence, a written domain will not be disturbed by any external stray field.

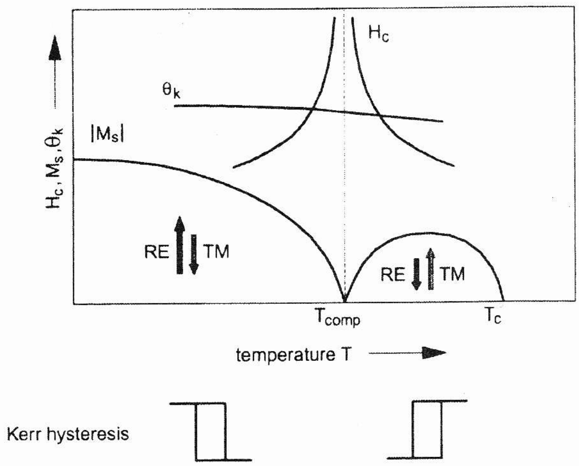


Fig. 4 Magneto-optical properties of amorphous rare earth (RE) and transition metal (TM) thin films. (M_s: saturation magnetization; θ_k: Kerr rotation; H_c coercitivity) [3]

An example for different TbFeCo films is shown in figure 5 [6]. Within a small range of composition the compensation temperature changes from zero to a value above Curie temperature. For the stability of the domains a compensation temperature near room temperature is favourable which can be obtained by a Tb content of approximately 25 %. The composition influences also the Curie temperature T_C but in a much smaller range. A Curie temperature near 200 °C is convenient for the writing process. For a given Tb content the Curie temperature can be slightly shifted to higher values by substitution of Fe by Co [5].

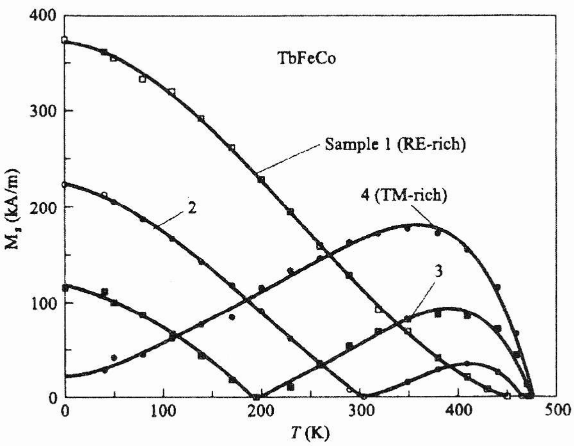


Fig. 5 Magnetization M_s of four TbFeCo films with different compositions; sample (1): $Tb_{29,9}$ $Fe_{2,6}$ $Co_{7,5}$; (2): $Tb_{27,2}$ $Fe_{65,5}$ $Co_{7,5}$; (3) $Tb_{23,6}$ $Fe_{67,6}$ $Co_{8,8}$; (4) $Tb_{21,2}$ $Fe_{71,9}$ $Co_{6,9}$ [6]

The Kerr effect required for read out is related to interband and intraband transitions of the RE/TM alloy. For wave lengths between 620 and 780 nm which are commonly used for read out, the main contribution comes from the 3d electrons of the transition metals. In the temperature range near the compensation temperature the Kerr rotation Θ_K varies only slightly according to the variation of the magnetization of the TM subnetwork. An external field, however, acts on the net magnetization, which changes from a RE dominated behaviour below the compensation temperature to a TM dominated behaviour above the compensation temperature. Hysteresis loops determined by MOKE, therefore, change their sign when the temperature passes the compensation temperature T_{comp} (figure 4).

A very important contribution to noise comes from irregularities of the written domains. They depend on the composition as well as on the writing conditions. In figure 6 this is demonstrated for some test structures observed in Tb/Fe multilayers. Domains which are formed spontaneously have normally an irregular shape (figure 6a). By using laser pulses of 20 µs pulse lengths and various power levels circular domains can be written in a film having H_c = 170 kA/m. Depending on the power level the diameter can be varied between 5 µm and 1 µm (figure 6b). The regularity of the domains depends also on the magnitude of the bias field during the writing process (figure 6c). For a pulse length of 10 µs and a power level of 1.8 mW the field must be above 15 kA/m otherwise a granular substructure is observed within the domains. In figure 6d a domain structure is shown which is obtained by magnetic field modulation. A circular domain can be partially overwritten when the laser spot is slightly shifted and the bias field is reversed from one direction to the opposite. The result is a track of crescent like domains. It is obvious, that a high recording density along the track can be obtained in spite of a relatively large diameter of the individual domain. This type of recording is applied in the present generation of the MiniDisc.

A principle limitation for the recording density is the optical diffraction. The diameter d of the diffraction pattern produced by the objective lens during writing and reading is given by

$$d = 1{,}22\ \lambda/NA \tag{3}$$

where λ is the wavelength of the radiation (at present between 780 nm and 620 nm) and NA is the numerical aperture of the objective lens of the optical head. The writing process is not so critical because the size of the written domain depends mainly on the relation between the applied bias field H_b and the temperature distribution of H_c produced by the laser pulse (cf. figure 6b).By appropriate conditions domains smaller than the optical limit d can be created. The main problem comes from the reading process because it is not possible to distinguish very small domains in a distance below (d/2). It is assumed, that the problem can be overcome in near future by magnetically induced super resolution (MSR) or related techniques (see section 4). A more straight forward solution would be the application of a green or blue laser instead of the present red and infrared lasers. In near future semiconductor lasers will be available with wavelengths of 428 nm (blue) which would allow an increase of recording density by a factor 3.8 by a linear reduction of the dimensions. However, for the present available RE/TM media the figure of merit drops rapidly with decreasing wavelengths. The most promising candidates for green and blue laser radiation are Co/Pt or Co/Pd multilayer structures with a typical composition 25x(0.4 nm Co + 1.9 nm Pt) [2, 4]. Although laboratory experiments have been successfully performed it is an open question, how a large number of discs with such a complicated structure can be produced in an industrial scale.

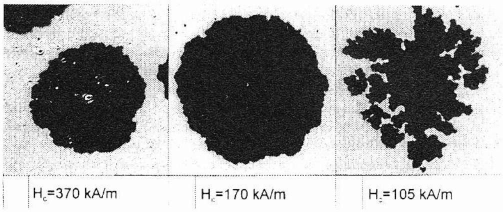
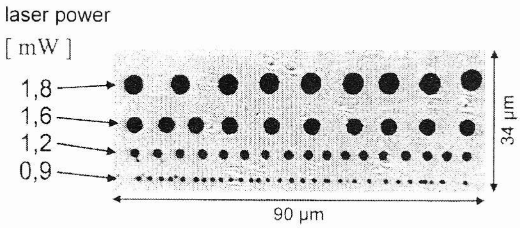
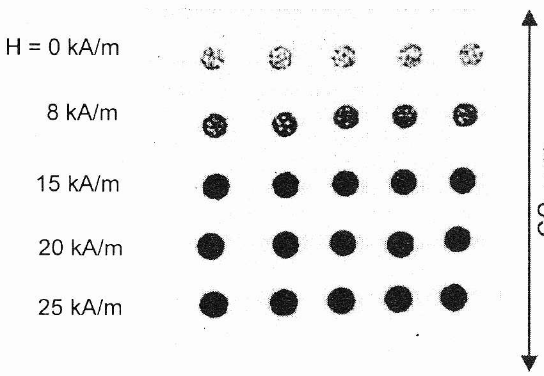


Fig. 6 Magnetic domains in Tb/Fe multilayers observed by Kerr microscopy (λ=680 nm)

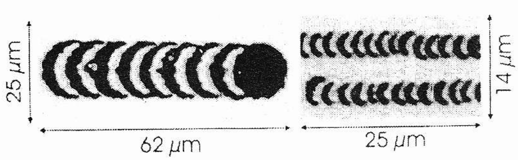
a) Spontanously formed domains in films with different coercitivities H_c



b) Thermomagnetc writing of domains in the film with H_c=170 kA/m by variation of the laser power at a pulse length of 20 µs



c) Thermomagnetic writing of domains by variation of the bias field H_b at a laser power of 1,8 mW and a pulse length of 10 µs



d) Demonstration of domains written by magnetic field modulation

4 Application of exchanged coupled layers

4.1 Basic principles

As already explained the standard MO discs have two drawbacks: The limited access time due to the erasing process and the limited recording density due to the optical diffraction. In both cases exchange coupled layer systems can overcome the restrictions. They allow laser intensity modulation for direct overwrite (LIM-DOW) and magnetically induced super resolution (MSR) [2-4, 7-9].

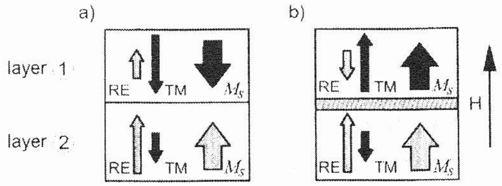


Fig. 7 Subnetwork magnetizations of the RE and TM components and net magnetization M_s of Exchange Coupled Double Layers (ECDLs) with antiparallel coupling; a) ground state without external field; b) saturation in an external field H [3]

An exchanged coupled double layer (ECDL) with antiparallel coupling is shown in figure 7. It consists of two layers with different compositions where layer 1 is TM dominated and layer 2 is RE dominated. In the ground state the exchange coupling of the two RE subnetworks as well as of the two TM subnetworks is very strong. As a consequence the net magnetizations are opposite to each other (antiparallel coupling). In a sufficiently high saturation field H the net magnetizations become parallel and the subnetwork magnetizations are opposite to each other. Therefore, an interface wall with wall energy σ_w is formed. When the coercivity of both layers is sufficiently high this situation may be stable also in an opposite external field. By switching of one layer the wall disappears and the wall energy is released. Therefore, switching takes place not at the coercivity H_c but at switching fields

$$H_s = H_c + (\sigma_w/2\, M_s\, t) \quad \text{or} \quad H_s = H_c - (\sigma_w/2\, M_s\, t) \tag{4}$$

where t is the thickness of the film. The sign (+) is related to the creation of a wall, and the sign (-) to wall annihilation. Figure 8 shows the switching fields of an ECDL with antiparallel coupling measured by MOKE from both sides of the film. Layer 1 is TM dominated and layer 2 is RE dominated. For the measurement, the external field was increased from negative saturation (initial state) to positive saturation (final state) at different temperatures. Note, that below a transition temperature T_s firstly layer 2 switches and then layer 1 whereas above T_s the switching takes place in an opposite sequence.

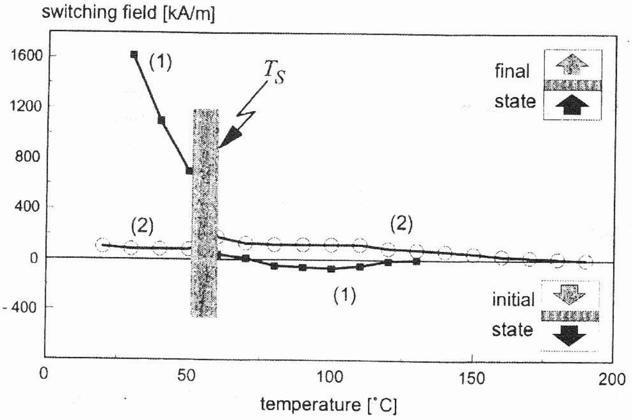


Fig. 8 Switching fields of an ECDL with antiparallel coupling as a function of temperature [3]

A behaviour as shown in figure 8 can be used to obtain LIM-DOW in ECDLs. Layer 1 acts as a memory layer where the information is stored. Layer 2 is a so called reference layer which is necessary to write a new information into the memory layer only by applying a laser pulse with high or low power level. The energy for switching comes partially from the release of the wall energy which is triggered by the laser pulse. The procedure was firstly proposed by Saito (see article of Saito in reference [2]) and is explained, for instance, in [3, 7]. Switching field diagrams as shown in figure 8 can be considered as phase diagrams which define stable magnetization configurations of the ECDL. They can be used to find appropriate bias fields and temperature ranges to perform a reliable high power or low power process [9].

4.2 Magnetically induced super resolution (MSR)

The resolution of conventional optical instruments is limited by diffraction as explained by equ. (3). However, this limit can be overcome by apertures the diameter of which is much smaller than the optical wave length. When the aperture is shifted over the sample in a very closed distance the transmitted intensity allows the detection of details below the optical limit. This technique, for instance, is applied in the scanning near field optical microscope (SNOM). ECDLs allow to transfer the principle of nearfield optics also to the magneto optical readout process. This is the basic idea of magnetically induced super resolution (MSR).

As an example MSR by central aperture detection (CAD) is shown in figure 9. The information is stored in the memory layer TbFeCo by magnetic domains much smaller than the diffraction spot of the laser. A readout layer consisting of GdFeCo has an inplane magnetization at modest temperatures, but may switch to a perpendicular magnetization in a temperature range above T_1. The domain structure of the memory layer is masked by the readout layer in the area where the temperature is below T_1 because the polar Kerr effect is sensitive only for perpendicular magnetization. If the maximum temperature T_2 is adjusted appropriately only a very small area of the readout layer has a perpendicular anisotropy. Within this area the information of the TbFeCo film is copied into the readout layer by exchange coupling and can be detected by the reflected light. The central part of the laser spot, therefore, forms a very small aperture which is shifted during the disc motion over the information stored in the memory layer. The intensity modulation of the reflected light corresponds to structures which are smaller than the diffraction limit of the laser beam.

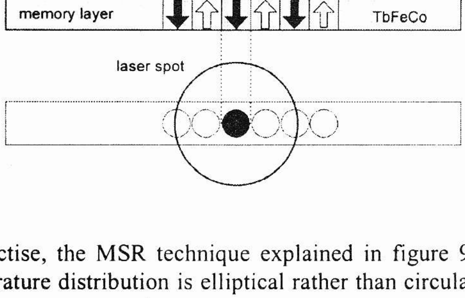


Fig. 9 Principle of magnetically induced superresolution (MSR) by central aperture detection (CAD) [7]

In practise, the MSR technique explained in figure 9 has to be modified due to the fact, that the temperature distribution is elliptical rather than circular because of the motion of the disc. This leads to front aperture detection (FAD) or rear aperture detection (RAD) which were initially proposed by Japanese authors in 1991 (see articles by Koneko in [2, 4]; qualitative descriptions are given in [3, 8]). In addition, there are other concepts to improve the resolution beyond the standard optical limit for instance by magnetic amplifying MO systems (MAMMOS) or by solid immersion lenses (SIL) [2, 4, 7, 8].

At present a 5.25 inch double sided disc has a capacity of 5.2 GBytes. Compared with the first generation put on the market in 1988 this is the 8X capacity. The main progress was achieved by a systematic reduction of the linear dimensions of the bit area. The track pitch, for instance, was reduced from 1.6 μm to 0.85 μm. Other contributions came from better coding methods and slightly smaller wave lengths. Further improvements can be expected from land and groove recording (factor 2X) and, in particular, from MSR techniques (factor ≥ 2X) before eventually the blue laser will be applied.

5 References

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