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Present and future of magnetooptical recording materials and technology

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Abstract

Erasable optical information storage from amorphous rare earth-transition metal (RE-TM) alloys media has led to impressive improvements towards hyper high density recording in the past five years. Write/erase and readout processes are based on light-induced thermomagnetic switching of magnetic domains and magnetooptical (MO) Kerr effect, respectively, in ferrimagnetic films exhibiting a uniaxial magnetic anisotropy. The route towards ultrahigh optical areal densities was open from the beginning of the nineties from two key technologies related to near field optical techniques and RE-TM exchange-coupled bi, tri- and multilayers. The performances of the MO media depend on the types and states of these multilayers with perpendicular or mixed (perpendicular and planar) anisotropies which change with the temperature and the applied field. The development of the thermomagnetooptical materials is discussed with reference to their magnetic and MO properties to increase the density storage. © 1998 Elsevier Science S.A.

Keywords: Magnetooptical recording; Multilayers

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1. Introduction

The magnetic recording density has increased by a factor 10^6 since the first rigid disk introduced on the market by IBM in 1957 (Ramac DASD system) with the magnetic bit length now down to 0.1 μm currently detected by flying magnetoinductive and magnetoresitive heads. Optical recording with the interesting removability and head crash free characteristics was proposed more recently with different types corresponding to prerecorded (audio, video and data CD-ROM), write-once read many (WORM) and erasable/rewritable disks. Future storage requires increasing capacity with very high areal density media which induces a strong competition between the usual magnetoinductive rigid disks without removability and removable optical disks. The magnetooptical (MO) storage combines the characteristics of magnetic and optical recordings with unlimited write/erase processes of nonvolatile recorded data, contactless write/read head from light focused millimeters away from the media which allows removability and prevents head crash. As a conventional Winchester system, the rigid MO disk can rotate at a speed up to 10^4 RPM giving high data rates. MO media offers bit density of a removable disk (1997: 8 Gbit cm^{-2}) with erase and rewrite possibilities. Data storage in structural phase change materials with reversible transitions under light heating from amorphous to crystalline states, which results in strong change of reflectivity used for reading, is alternative to MO media for rewritable optical memories [1]. These phase change systems, introduced recently in the market for data and video (DVD) storage, have simple monolayer disk structure and high readout signal, but phase change cyclability and density seem to be limited compared to MO materials. Therefore to maintain their competitive advantage with phase change media, researchers have been pushing in the recent past towards ultra high density MO storage. As a breakthrough research a 30 GB capacity 5-inch MO disk with red light was announced recently with expected extension to 90 GB with blue laser in the near future [2].

The route towards ultra or hyper high MO densities started at the beginning of the nineties from two key technologies related to near field optical microscopy (NFOM) and RE-TM exchange-coupled di, tri- and multilayers (ECDL, ECTL and ECML). The present and future of MO technology and materials are reviewed and discussed in this paper.

2. Physical limits towards hyper MO storage

Writing in conventional longitudinal magnetic recording is achieved in high coercivity media by a local magnetization reversal induced at room temperature by a strong switching field (H_s~$3H_c$) produced by a magnetoinductive head in-contact to or flying at submicronic

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distance from the media. In MO media the magnetization reversal for writing is induced by a small switching field (H_s~200 Oe) after the media coercivity is reduced by a local heating from a laser beam focused at the diffraction limit (Fig. 1). The erase process, based on the same thermomagnetic effect, required opposite field $-H_S$. Reading of the data uses the MO Kerr effect which can discriminate adjacent magnetic bits associated with information stored in a perpendicular magnetization film, from the opposite sign of the light polarisation rotation detected with polarisation optics after reflection on the up- and down-oriented magnetic domains. Approaches to ultrahigh density up to 15 Gbit cm^{-2} (~100 Gbit in^{-2}) must be analyzed with respect to physical limits related to fundamental properties of magnetism and optics.

2.1. Magnetic limits

Magnetic storage is based on the magnetization reversal as observed in the two interesting but different situations corresponding to a structure of either polydomains separated by domain walls or single domain particles. The fundamental limit of multidomain structure is given by the domain wall (DW) thickness $\Delta=4(A/K_u)^{1/2}$ where A is the exchange constant and K_u the uniaxial anisotropy. Some materials with very large K_u present narrow DW down to a few atomic distances which could support a theoretical huge density D_s of about 10^4 Gbit cm^{-2}. A more realistic situation is obtained from the minimum size for stable magnetic domains given by:

$$d_{\min} = \sigma/(M_s H_c) = 4(AK_u)^{1/2}/M_s H_c. \tag{1}$$

This relation describes the competition between the wall energy σ which induces a shrinking force to reduce the domain size and the coercive energy of frictional character which stabilizes the wall [3]. Amorphous RE-TM alloys may exhibit very strong coercivity higher than 20 kOe around the compensation temperature T_{cp} associated with their ferrimagnetic structure and domains in the 10 nm range could be possible which results in a theoretical areal density $D_s = 1/2d^2_{\min}$ up to 500 Gbit cm^{-2}. Until now only areal density of 8 Gbit cm^{-2} corresponding to recording of 80 nm-diameter domains in amorphous RE-TM alloys has been reported [2]. Analysis of thermal stability shows that these materials can easily support stable domains with diameter as small as 40 nm ($D_s = 30$ Gbit cm^{-2}).

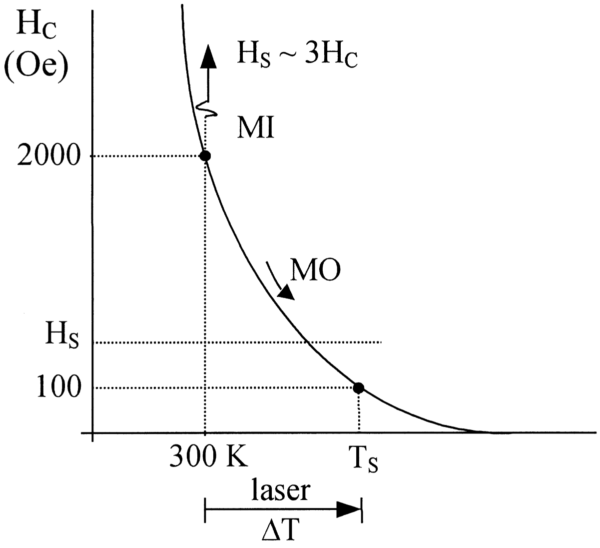


Fig. 1. Writing in MO media from a thermomagnetic process.

Due to the fine grain polycrystalline structure of the Co-based longitudinal media, the magnetoinductive recording is limited by super-paramagnetism processes. These processes are not present in the MO storage using homogeneous amorphous RE-TM alloys having continuous exchange coupling in materials with perpendicular anisotropy. By reducing, for higher densities, the grain volume V the single grain anisotropy energy $K_u V$ can be too small with respect to the thermal energy kT which destabilizes the magnetization direction of the recorded data. It was reported recently that due to super-paramagnetism a stable storage density of 15 Gbit cm^{-2} cannot be expected in longitudinal magnetic polycrystalline media [4].

It is concluded that MO recording with amorphous RE-TM alloys can achieve 15 Gbit cm^{-2} or higher densities which is not expected for longitudinal magnetoinductive recording based on fine grain polycrystalline materials.

2.2. Optical limits

Bit density in optical recording (including CD-ROM, WORM and erasable media) is limited by the laws of diffraction of optics. However, for the writing process in MO media it is shown that there is no critical problems to create magnetic domains with size smaller than the Rayleigh resolution limit. On the other hand, the readout process has a more critical dependence on the Rayleigh limit which allows the detection of domain with a minimum size given by:

$$d_{\mathrm{Rayleigh}} = 1.22\lambda/\mathrm{NA} \tag{2}$$

where λ is the light wavelength and NA the numerical aperture of the objective lens (Fig. 2(a)). However, from experiment it is shown that the minimum size of detected domains is half the Rayleigh limit:

$$d_{\min} = 0.66\lambda/\mathrm{NA}. \tag{3}$$

With the usual IR laser diode ($\lambda = 780$ nm) and NA = 0.6, the expected areal density $D_s = 1/2d^2_{\min}$ is 80 Mbit cm^{-2} which is far from an ultrahigh density storage.

2.3. Alternative for hyper MO storage

An increase of the density from the reduction of the domain size requires for detection higher NA or/and

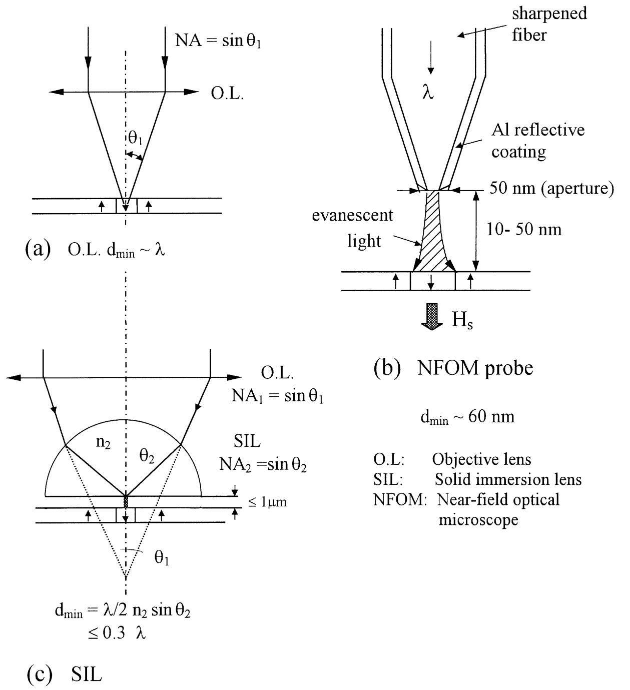


Fig. 2. Thermomagnetooptical writing from a usual objective lens (a) to near-field optical techniques by NFOM (b) and SIL (c).

shorter λ (Eq. (3)) from blue to UV light giving bit size in the range of the wavelength ($d \sim \lambda = 0.4$ and 0.2 μm) and densities around $D_s = 0.3$ and 1.2 Gbit cm^{-2}. Despite the strong R/D in the nineties, reliable CW low-cost solid state blue lasers will not be available for many years. Fortunately alternatives to blue light to overcome the diffraction limit were proposed in the recent past from two original key technologies based on near-field optical techniques and the so-called magnetically-induced super-resolution (MSR) detection. These breakthrough technologies are developed from usual IR light and conventional first generation RE-TM magnetooptical media.

2.3.1. Near-field optical recording

Two main approaches based the first based on a scanning near-field optical microscope (SNOM) and the second on a solid immersion lens (SIL) effect are presently being investigated to succeed the ultrahigh density near-field MO storage. The demonstration of a near-field MO recording of long-term stable 60 nm domains was first reported by Betzig et al. in Co/Pt multilayers [5]. Writing and recording processes are performed from an evanescent near infrared light ($\lambda = 780$ nm) emitted by the small aperture (50 nm diameter) of a SNOM probe made from a sharpened optical fiber as described in Fig. 2(b). A constant spacing gap from 10 to 50 nm between the probe and the MO media is controlled from the usual noncontact mode operation of the atomic force microscope (AFM). An alternative to the thermomagnetic writing process induced by the evanescent light has been reported by Nakamura from a local heating produced by a tunnel current in the RE-TM sample with recording of stable 60 nm domains and potential density of 30 Gbit cm^{-2} [6]. However, due to the narrow spacing gap, a recording system with sufficiently high data rate has to be developed for practical use of the SNOM in the future.

Focusing from conventional objective lens (Fig. 2(a)) has been strongly improved by the use of a "solid immersion lens" flying at short spacing gap in the micron or submicron range from the disk surface [7]. Similar to liquid immersion lenses, first used to increase image magnification by placing a drop of oil on the microscope objective lens, the SIL requires a highly refractive solid glass lens as shown in Fig. 2(c). A near-field effect is observed when the hemispherical SIL lens is closed (within a wavelength of light) to the media surface. Light is introduced to an unaberated focus inside the SIL, increasing the numerical aperture NA by a factor of n_2 (n_2 is the refractive index of the SIL) which allows the detection of domains with a minimum size given by:

$$D_{\mathrm{SIL}} = 0.61\lambda/n_2 \sin\theta_1. \tag{4}$$

With high refractive index between 2.2 and 2.5 the light wavelength inside the SIL is reduced by a factor from 2 to 3 and therefore can be focused onto a much smaller area in the range $d_{\mathrm{min}} \sim 0.3\lambda$–$0.5\lambda$. By using the SIL technique with IR light source ($\lambda = 830$ nm), Terris et al. [7] have recorded in RE-TM monolayer media 230 nm-size domains (areal density ~1 Gbit cm^{-2}) which is better that could be obtained with a blue laser. The SIL lens can easily halve 680 nm (red) and 400 nm wavelengths (blue) towards the UV range which opens the route to ultrahigh densities ($D_s > 5$ Gbit cm^{-2}) with recorded nano-domains. From the present state-of-art of the SIL technology a tenfold bump in storage capacity (over 20 GB per surface of 5-inch MO disk) is expected in the next couple of years [8].

2.3.2. Magnetic super-resolution

A very efficient technique for the readout with red or IR light of very small domains from submicronic (200 nm) down to nanometric (80 nm) range was first proposed in 1991 by Ohta at al. from the use of a magnetically-induced super-resolution (MSR) detection process [9]. Such a technique has been developed in many laboratories by using exchange-coupled bi-, tri- and quadrilayers. The MSR process can be easily understood from a simple model of ECDL (Fig. 3(a)) based on a perpendicular magnetization memory layer (M_1) exchange-coupled with an in-plane magnetization readout or aperture layer (M_2) as proposed by Murakami et al. [10]. The in-plane M_2 is due at room temperature to the negative value of the effective anisotropy $K_2 = K_{u2} - 2\pi M_2^2$ (K_{u2} is a positive intrinsic uniaxial anisotropy) induced by the high value of M_2. During the readback the irradiation by a moderate laser power ($P_1 \approx 3$ mW) produces a Gaussian heating profile

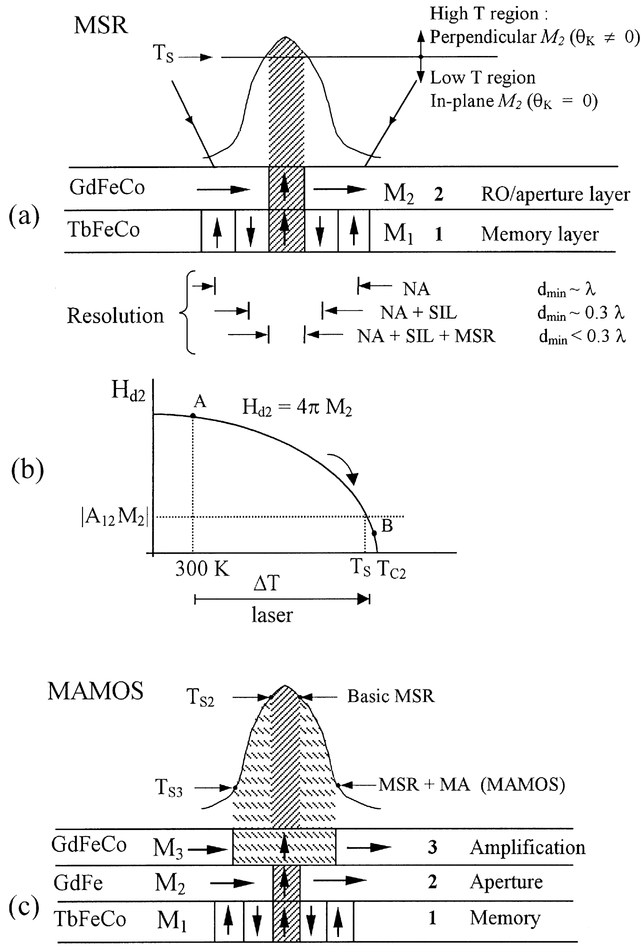


Fig. 3. Basic MSR (a) and MAMOS (c) detections using a local demagnetizing field in an in-plane layer (b).

which induces in the readout layer two regions separated by a critical switching temperature T_s corresponding to the sign reversal of K_2 ($K_{u2}=2\pi M_2^2$) with the temperature as reported for a GdFeCo monolayer in Fig. 4. In the high-T region ($T>T_s$) the spontaneous perpendicularly-oriented magnetization ($K_2>0$) of the readout layer is also stimulated by the interlayer exchange field $A_{12}M_1$ induced by the memory layer (Fig. 3(b)). Such a local rotation of M_2 by the exchange coupling opens an optical aperture for the reading by MO Kerr effect of only one domain. On the other hand, in the low-T region ($T<T_s$)M_2 keeps its in-plane orientation ($K_2<0$) which prevents any bit detection. Such a local thermomagnetic-induced copy of domains by a magnetization switching is very efficient for the discrimination of very small magnetic bits. Detection of 200 nm domains by red and near infrared light is now currently performed in laboratories. However, the decreasing size of the domains induces a parallel reduction of the readback signal current I_d produced by the photodetectors:

$$I_d = \eta k P_0 R \sin 2\theta_K \tag{5}$$

where θ_K and R are the MO Kerr rotation and the media reflectivity. η and P_0 are the sensitivity of the photodiode and the average incident light intensity on the media. The constant k describes the proportion of the light intensity detected after reflection by a single domain and restricted by the limit of the aperture size. To improve the signal-to-noise ratio (SNR) it is necessary to increase this constant which is proportional to the ratio:aperture diameter/Airy diffraction spot diameter. Impressive improvement of the SNR by an artificial increase of the aperture has been succeeded recently from a magnetic amplification of the MO signal (MAMOS) based on a dynamic expansion effect of the domains in trilayer MSR media with double in-plane magnetic layer M_2 and M_3 corresponding, respectively, to intermediate (or aperture) and readout layers as described in Fig. 3(c) [2]. As discussed in what follows a high value room temperature magnetization in planar layers M_2 and M_3 is obtained from Gd-based RE-TM alloys. From the appropriate choice of the chemical composition of these layers, the magnetization changes from in-plane to perpendicular direction by increasing T from the room temperature, first in the readout layer at the switching temperature T_{s3} and later in the intermediate layer at T_{s2}, are in agreement with the model we have calculated for the trilayers $Gd_{28}Fe_{43}Co_{29}/Gd_{34}Fe_{66}/Tb_{20}Fe_{64}Co_{16}$ [11]. It is seen that when the aperture area with the radius r_2 is induced in the intermediate layer by the laser irradiation, a perpendicular magnetization area with a larger radius $r_3>r_2$ is already stimulated in the readout layer. The copy by the intermediate layer of only one domain from the memory layer can be transferred with a large dynamic expansion in the readout layer. The expansion ratio r_3/r_2 is in the range from 2 to 3 which may result in a magnetic amplification of the MO signal by a factor higher than 4. A 30 GB capacity per 5-inch disk surface based on such a magnetically-induced amplification of the MO signal with 80 nm domains detected with a

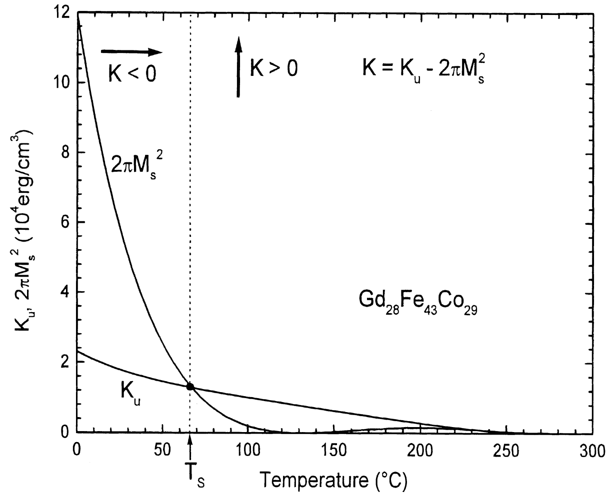
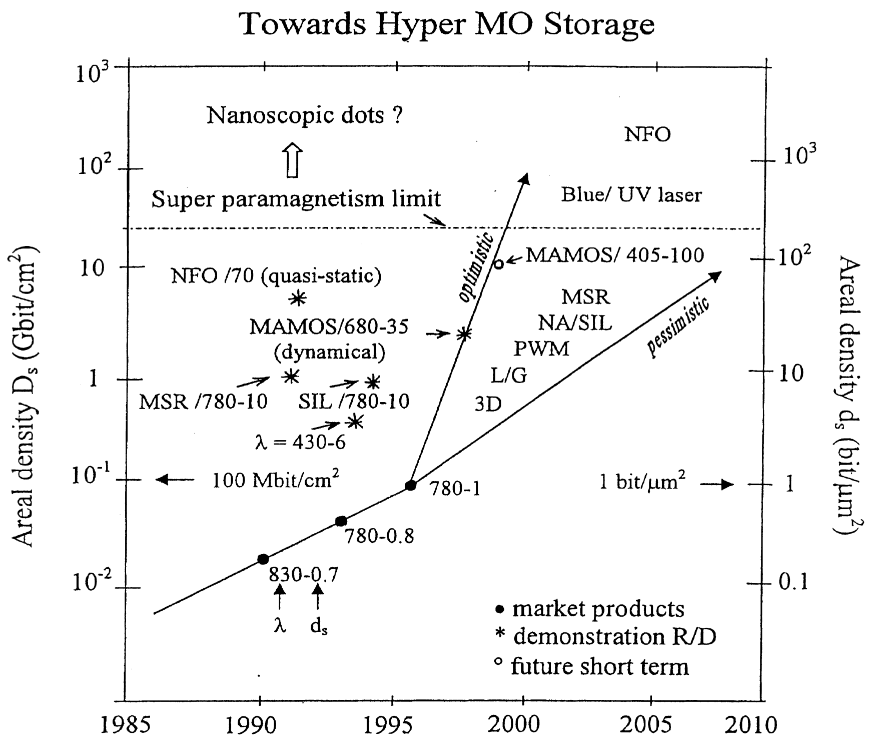


Fig. 4. Temperature-induced reorientation of the magnetization in GdFeCo films.



PWM:	Pulse Width Modulation
L/G :	Land/ Groove
IOH:	Integrated Optical Head
NA/SIL:	Numerical Aperture/Solid Immersion Lens
MSR:	Magnetic super-resolution
NFO:	Near field optical recording
MAMOS:	Magnetic amplification of MO signal

Fig. 5. Present and future evolutions of the MO storage.

red laser ($\lambda=680$ nm) has been reported this year with expected capacity up to 90 GB by using blue light in the near future [2]. The present and the expected evolution of the MO recording is reported in Fig. 5.

3. Exchange-coupled multilayers

ECML (up to five layers) with amorphous RE-TM alloys are currently used in MO recording, not only for ultrahigh density readout from the MAMOS process, but also to reduce the write magnetic field (bilayers) and to increase either the MO effect at short wavelength (trilayers) or the data transfer rate from a direct overwriting (DOW) process (up to five layers).

RE-TM alloys in most of the MO layers are heavy RE-based (Gd, Tb, Dy) materials with a ferrimagnetic structure governed by antiferromagnetic coupling between RE and TM and a compensation temperature T_{cp} with $M_{RE} \gtrless M_{TM}$ for $T \lessgtr T_{cp}$. The basis properties of ECDL arise from the microscopic interlayer exchange coupling which induces under zero external field spontaneous parallel orientations between the RE moments and between the TM moments of the two layers. Depending on the temperature with respect to T_{cp1} and T_{cp2}, two types of macroscopic magnetization structures described from the total saturation moments $M_{1,2}=M_{RE1,2}-M_{TM1,2}$, where $M_{RE1,2}$ and $M_{TM1,2}$ are the RE and TM moments in the films 1 and 2, respectively, are defined as described in Fig. 6 for ECDL with only perpendicular anisotropy (case a) or mixed (perpendicular and in-plane, case c) anisotropies. Whatever the anisotropy sign, in a type 2 (or P for parallel) ECDL the RE (or TM) moments are dominant in both films 1 and 2 and the macroscopic moments M_1 and M_2 are parallel as shown in Fig. 6 for $T<T_{cp1}$, T_{cp2} (or $T>T_{cp1}$, T_{cp2}). On the other hand for $T_{cp1}<T_{cp2}$ the RE (or TM) moment is dominant in one layer and the TM (or RE) moment is dominant in the second layer which induces a type 1 or A (antiparallel) ECDL with an antiparallel orientation of the macroscopic moments M_1 and M_2.

Near T_{cp1} and T_{cp2} the coercivities H_{c1} and H_{c2} increase strongly ($H_c \sim K_u/M_s$) and under increasing external field many magnetostructural transitions depending on the respective values of H_{c1} and H_{c2} can be observed as described in Fig. 6(b) for the type 2/P ECDL with moment reversals first in film 2 and later in film 1 since $H_{c2}<H_{c1}$. The switching field H_s between two states is determined from the switching layer coercivity corrected by the field

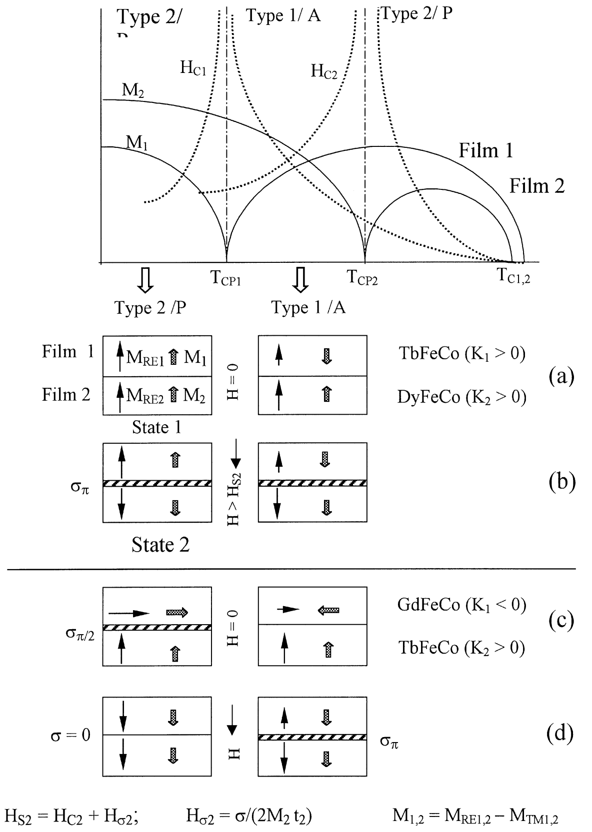


Fig. 6. Types 1 and 2 of ECDL with perpendicular (a,b) and mixed (c,d) anisotropies.

required to create or destroy an interfacial wall corresponding to a pseudo-Bloch wall when the RE and TM moments have to rotate through the interface [12]. ECDL with mixed anisotropies present similar properties with magnetostructural transitions depending on the intrinsic parameters of the layers.

Static and dynamic properties of ECML can be determined from the magnetization profiles and reversals as calculated from a discontinuous model of the magnetization based on very thin magnetic sheets [13,14]. Due to the interlayer exchange coupling in both perpendicular and mixed anisotropy ECML, it is shown that a bias or exchange field can be induced from one layer to the next one which modifies strongly the structural and dynamical properties of the layers. Very strong ‘‘capping’’ fields higher than 5 kOe are observed from amorphous RE-TM alloys [14] and can be used to reduce the writing field in MO storage or to suppress a multidomain structure in soft magnetoinductive and magnetoresistive thin film heads.

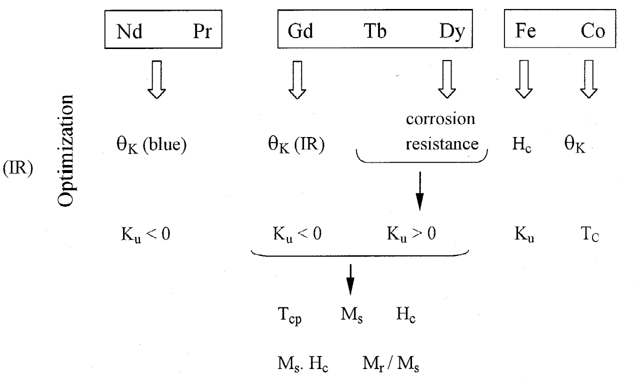
4. Magnetooptical recording materials

MO materials for ultrahigh density recording require, from the write, read and storage processes, a lot of well controlled but not easy to meet all together magnetic MO and optical properties such as: a positive uniaxial anisotropy to store perpendicular domains which can be read from polar Kerr effect; a large $M_s H_c$ product at room temperature for the high stability of submicronic domains; a high squareness at high temperature for short switching during the write/erase processes; a Curie temperature in the range 400–600 K for long term domains stability; a high optical absorption to use low laser power during writing; a high figure of merit $R\theta_K^2$ (R: reflectivity) for the optimal reading process and a low level of the noise induced by reflectivity and refractive inhomogeneities or light diffusions from grain structures and boundaries.

In spite of its unusually large Kerr rotation MnBi, first investigated for MO recording, was left because of a low SNR produced by the light diffusion from the grain boundaries and a poor structural stability with the temperature [15]. Different classes of materials have been proposed later corresponding to ferrimagnetic oxides with garnet and spinel structures, the amorphous RE-TM alloys and more recently the Co/Pt multilayers. The garnet and Co/Pt present a large figure of merit at short wavelength in the blue range. However, similar to MnBi these materials have poor SNR caused by their polycrystalline structure and too low coercivity and uniaxial anisotropy.

On the other hand, the RE-TM alloys can exhibit all the basic properties required for ultrahigh density MO recording, such as high positive uniaxial anisotropy and coercivity associated with the ferrimagnetism of the material, a large Kerr rotation similar to that of MnBi even at short wavelength and no grain noise from an amorphous defect-free and mirror-like surface film. From the first GdCo alloy proposed by Chaudhari et al. [16], many binary, ternary and quaternary RE-TM mono- and multilayers have been investigated to optimize the intrinsic parameters such as K_u, H_c, M_s, θ_K.... The coercivity at room and high temperatures depends on the compensation temperature (Fig. 6) which is strongly sensitive to the RE content. As summarized in Table 1, the composition (types and contents of RE and TM atoms) can be easily designed to

Table 1
RE and TM for MO media optimization



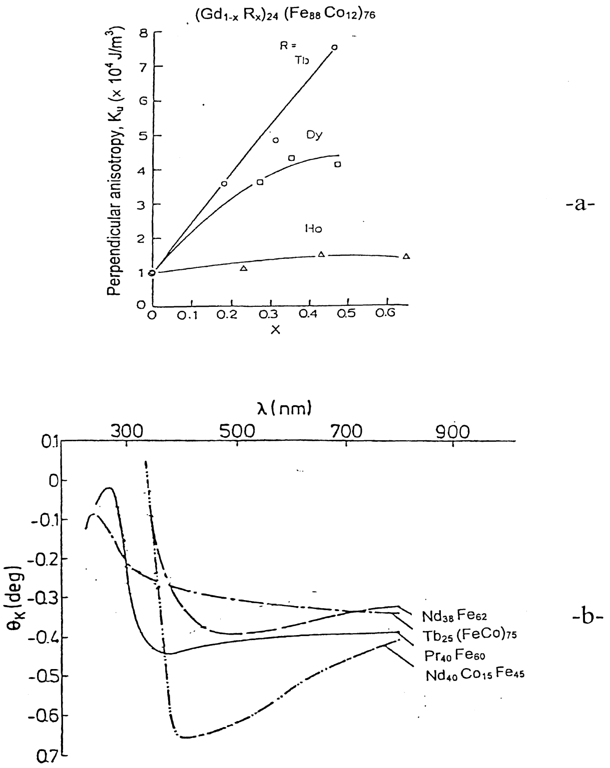


Fig. 7. Perpendicular anisotropy (a) and Kerr rotation in RE-TM films (b).

optimize the MO media with respect to the write/erase, reading and storage processes. Strong perpendicular anisotropy requires heavy RE (Tb, Dy) but in-plane anisotropy is obtained from Gd-based alloys (Fig. 7(a)) [17]. Substitution of Dy for Tb improves strongly the corrosion resistance of the MO media [18]. T_{cp} and T_c increase with the RE and Co contents, respectively, which give an easy way to adjust the coercivity [18]. The MO Kerr effect of heavy RE-based alloys (TbFeCo, DyFeCo . . .) is poor in the 400 nm wavelength range. Substitution of light RE such as Nd or Pr for Tb or Dy increases strongly the MO activity in the short wavelength range as reported in Fig. 7(b) [19]. However, these materials have smaller perpendicular anisotropy with in-plane magnetization orientation due to the high saturation magnetization associated with the ferromagnetic coupling between the RE and TM moments. The exchange coupling between a low anisotropy high Kerr rotation layer (readout) with a high perpendicular anisotropy layer (memory) would be an alternative for short wavelength detection from ECDL with mixed anisotropies. The magnetic and MO characteristics of RE-TM alloys for MO storage are summarized in Table 2.

Table 2
Magnetic and MO characteristics of RE-TM alloys for MO storage

Alloys	Chemical Composition		K_U	T_C	$M_S H_C$	θ_K
Binary monolayers 1973 - 1983	GdCo	1973	TS	TL	TS	ML
	TbCo	1983	L	TL	M	ML
	GdFe	1980	TS	M	TS	M
	TbFe	1976	L	TS	ML	L
Ternary monolayers 1983 - 1989	GdTbFe	1983	L	M	L	M
	GdTbCo	1983	L	L	L	M
	TbFeCo →	DyFeCo	VL	L	L	ML
	1983	1989				
	⇩	⇩				
Quaternary monolayers 1984 - 1993	GdTbFeCo	GdDyFeCo	VL	L	L	ML
	⇩	⇩				
	NdTbFeCo	NdDyFeCo (blue)	VL	L	L	ML
Bi/ternary trilayers	TbFeCo / NdCo / TbFeCo 25 nm 10 nm 5 nm		M : Moderate L : Large ML : Moderate large VL : Very large TL : Too large TS : Too small			

5. Conclusion

The development of ECML from amorphous RE-TM suitable for ultrahigh density rewritable optical storage has been quite impressive along the past five years and MO disks with direct overwriting, near-field optical process and magnetically-induced super-resolution detection are now available or close to being introduced onto the market. Hyper high capacity up to 30 GB per 5-inch disk surface has been demonstrated with red light with extension to 90 GB with blue light in the short term. The high performance media are based on ECML which require in the future improved RE-TM materials and further investigations on static and dynamical properties of magnetic multilayers.

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