APPLIED PHYSICS REVIEWS—FOCUSED REVIEW

Perpendicular recording media for hard disk drives

S. N. Piramanayagam[a)]
Data Storage Institute, 5 Engineering Drive 1, Singapore 117608, Singapore

(Received 27 October 2006; accepted 28 March 2007; published online 6 July 2007; publisher error corrected 12 July 2007)

Perpendicular recording technology has recently been introduced in hard disk drives for computer and consumer electronics applications. Although conceptualized in the late 1970s, making a product with perpendicular recording that has competing performance, reliability, and price advantage over the prevalent longitudinal recording technology has taken about three decades. One reason for the late entry of perpendicular recording is that the longitudinal recording technology was quite successful in overcoming many of its problems and in staying competitive. Other reasons are the risks, problems, and investment needed in making a successful transition to perpendicular recording technology. Iwasaki and co-workers came up with many inventions in the late 1970s, such as single-pole head, CoCr alloy media with a perpendicular anisotropy, and recording media with soft magnetic underlayers [S. Iwasaki and K. Takemura, IEEE Trans. Magn. **11**, 1173 (1975); S. Iwasaki and Y. Nakamura, *ibid.* **14**, 436 (1978); S. Iwasaki, Y. Nakamura, and K. Ouchi, *ibid.* **15**, 1456 (1979)]. Nevertheless, the research on perpendicular recording media has been intense only in the past five years or so. The main reason for the current interest comes from the need to find an alternative technology to get away from the superparamagnetic limit faced by the longitudinal recording. Out of the several recording media materials investigated in the past, oxide based CoCrPt media have been considered a blessing. The media developed with CoCrPt-oxide or CoCrPt–SiO_2 have shown much smaller grain sizes, lower noise, and larger thermal stability than the perpendicular recording media of the past, which is one of the reasons for the success of perpendicular recording. Moreover, oxide-based perpendicular media have also overtaken the current longitudinal recording media in terms of better recording performance. Several issues that were faced with the soft underlayers have also been solved by the use of antiferromagnetically coupled soft underlayers and soft underlayers that are exchange coupled with an antiferromagnetic layer. Significant improvements have also been made in the head design. All these factors now make perpendicular recording more competitive. It is expected that the current materials could theoretically support areal densities of up to 500–600 Gbits/in.^{2}. In this paper, the technologies associated with perpendicular recording media are reviewed. A brief background of magnetic recording and the challenges faced by longitudinal recording technology are presented first, followed by the discussions on perpendicular recording media. Detailed discussions on various layers in the perpendicular recording media and the recent advances in these layers have been made. Some of the future technologies that might help the industry beyond the conventional perpendicular recording technology are discussed at the end of the paper.
[DOI: 10.1063/1.2750414]

TABLE OF CONTENTS

[a)]Author to whom correspondence should be addressed; FAX: +65-67772406; electronic mail: prem@ieee.org

I. INTRODUCTION

Hard disk drives (HDDs) have been traditionally used in computers since the late 1950s when IBM introduced random access method of accounting and control (RAMAC). The first-generation hard disk drives were expensive and big but pioneered the random access feature for the main frame computers of that era. The hard disk drives improved over time and entered the personal computers in the 1980s. Recently, HDDs are also being commonly used in consumer electronics applications. MP3 players, video recorders, video cameras, game consoles, and many other devices are using HDDs to store information. Some analysts predict that by 2009 about 500×10^6 HDDs need to be produced in a year to satisfy the needs of computer and consumer electronics (CE) application. Such a growth in demand is good news for the HDD industry because, while the markets for HDD in computer applications may have saturated, the market in CE is a growth area.

The phenomenal advances made in the HDD technology have made such growth possible. The previous decade witnessed the doubling of HDD capacity almost every 12–18 months. Compared to RAMAC, which had a capacity of 5 Mbytes, the capacity of current hard disks at 750 Gbytes represents an increase in the capacity by a factor of about 150 000. While this number may not look that impressive, it is essential to note that the capacity of a HDD depends on the areal density (number of stored bits/in.^{2}), on the number of disks used, and on the area available in each disk. While RAMAC used 50 disks with a diameter of 24 in. to store information, current HDDs use 1 or 2 disks of 3.5 in. diameter or less to store information. Therefore, if we compare the areal density at which the data is stored, the increase from 2 kbits/in.^{2} (RAMAC) to 130 Gbits/in.^{2} (common specification for current HDDs) is 65×10^6 times larger. In other words, if we assume that a device with the features of RAMAC (50 disks of 24 in. diameter) was made with today's areal density, it would have a capacity of over 325 Tbytes. Such a tremendous increase in areal density helps in many aspects. (i) The cost per gigabit of data storage is reduced (as the production cost of HDD is maintained relatively the same). While this helps the consumer to buy storage at cheaper costs, the areal density increase also helps the HDD makers to maintain a competitive edge over other technologies such as flash memory or optical storage devices. (ii) Miniaturization of HDDs suits smaller consumer electronics devices without sacrificing the high-capacity needs. Therefore, in order to stay competitive in computer and consumer electronics applications, the HDD industry needs to constantly innovate and offer cheaper and reliable bits.

Until recently, the HDDs used longitudinal recording technology to store information. In longitudinal recording technology, the magnetizations that lie longitudinally (parallel to the disk surface) are used for storing information. Alternative technologies such as perpendicular recording, in which magnetizations lie perpendicular to the disk surface, were proposed in the late 1970s to overcome some of the potential problems with longitudinal recording.[1–3] However, longitudinal recording stayed competitive for all these years and delayed its rival technology. Only recently, HDDs using perpendicular recording technology were successfully released. The risks, problems, and investment needed in making perpendicular recording media were so huge compared to longitudinal recording that the companies in the USA almost neglected perpendicular recording. The research on perpendicular recording until the last century was limited mainly to several Japanese researchers from the industry and university.[2–12]

Nevertheless, the research on perpendicular recording media has been intense in the past five years and has received the attention of industry researchers worldwide.[13–20] The main reason for the current interest comes from the need to find an alternative technology to get away from the superparamagnetic limit faced by the longitudinal recording. Another reason for the enhanced interest in perpendicular recording technology comes from the progress in some of the materials and techniques used to produce better recording layers and soft underlayers (SULs), which would provide comparable or superior performance than the longitudinal recording media.[13,14,16,19,21] Significant improvements have also been made in the head design.[22,23] All these factors now make perpendicular recording more competitive. It is expected that the current materials could theoretically support areal densities of up to 500–600 Gbits/in.^{2}. In this paper, the technologies associated with perpendicular recording media are reviewed with some initial discussions on longitudinal recording. Due to the vast amount of data available in this area, it may not be possible to cite every possible work. Moreover, several review papers on perpendicular recording are available, which cover some of the earlier work.[24–30]

Therefore, the focus of the current review will be on the recent work related to perpendicular recording media.

The uniqueness of the current review lies in its tutorial format and in the way it is organized to report the progress in several functional layers of perpendicular recording media and the physics behind them. At first, a brief overview of magnetic recording in the longitudinal recording mode is provided. Then, the challenges faced by longitudinal recording media are presented. Section IV describes the initial research work on perpendicular recording technology. Various layers that make the perpendicular recording media and the recent advances in technology associated with these layers are discussed in Sec. V. Following the discussion on perpendicular recording media, some of the future media technologies that might help the industry to move beyond the limits of conventional perpendicular recording technology are discussed.

II. OVERVIEW OF LONGITUDINAL MAGNETIC RECORDING

Magnetic recording, which was invented by Paulsen a century ago, relies on two basic principles: (i) Magnets produce strong magnetic fields at the poles. This field can be used for reading information. (ii) The polarity of the magnets itself can be changed by applying external fields. This provides a possibility of writing information. Therefore, a magnetic recording device would have the following key components: a recording medium to store information, a writer head to produce localized magnetic fields (for writing information), and a read sensor to convert the magnetic field from the media to electrical (voltage) signals (reading information). There are many other components to position the head, to interpret the voltages into bits, and so on.

In the first few generations of hard disk drives, and in many of the tape storage devices, a particulate medium (which is essentially a mixture of magnetic particles in a binder) was used. A particulate medium cannot have a high saturation magnetization, as the saturation magnetization of the magnetic material will be diluted by the binder. In the earlier days, a high saturation (or remanent) magnetization was required from the recording media, as the signal produced will be proportional to the product of remanent moment and thickness of the media and the heads were not sensitive enough to detect a weak signal. Another problem was that the coercivity of the particulate media could not be tailored easily to meet the high-density requirements. Therefore, thin film media, which can provide high saturation/remanent magnetization and higher coercivity, were considered as alternative in the HDDs. Moreover, thin film media also provided smooth surfaces, as compared to that of particulate media. Therefore, particulate media were phased out from HDDs several years back. In this section, some of the requirements of longitudinal recording media and the ways they were achieved are described.

A. Small grain size

Thin film media are usually deposited by dc magnetron sputtering. Current recording media have several functional layers to achieve desired performance. However, the heart of the medium is the magnetic layer that stores the information. The magnetic layer produced by sputtering is a polycrystalline material. Therefore, the grains of the recording medium would have random orientations with respect to the film plane and with respect to the track direction as well. Moreover, they would also be arranged in random positions and sizes. Figure 1 is an illustration of the grains in a recording medium. The grains may have a random easy axis orientation as well as random grain sizes as depicted. Because of this randomness in the nature of the grains used in storing the information, a group of grains are used to store information. The signal-to-noise ratio (SNR) is approximately given by the expression

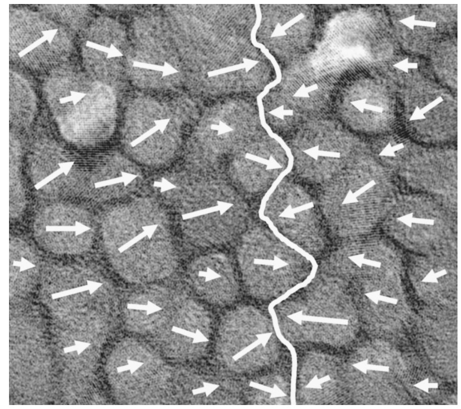

FIG. 1. Illustration of grains, the randomness of easy-axis orientations and the bit boundary.

$$\mathrm{SNR} = 10 \log(N), \tag{1}$$

where N is the number of grains in a bit. To some extent, the SNR at a particular linear density is an indicator of how reliably the bits could be read out at that linear density. Therefore, SNR is a key indicator of the recording performance of a recording medium.

Equation (1) indicates that increasing the number of grains would help increase the SNR. Therefore, one way to increase the SNR of the recording medium is to reduce the grain size and grain size distribution, which would increase the number of grains in the bit area. A lot of research work has been carried out along this direction to increase the SNR. Grain size reduction can be achieved by the use of seed layers and/or underlayers with small grain sizes or from the magnetic layer itself.[31–41]

B. Easy axis orientation parallel to the disk

Other approaches to improve the SNR of the recording medium are possible by looking beyond Eq. (1). Equation (1) assumes that SNR is proportional to the number of grains because of the randomness involved in the grain orientation and grain size. In the case of longitudinal media, the signal produced by the recording medium will depend on the component of magnetization that lies parallel to the track direction. If there are more grains, the component of magnetization along the track direction will also be higher. On the other hand, if the randomness can be minimized and if the

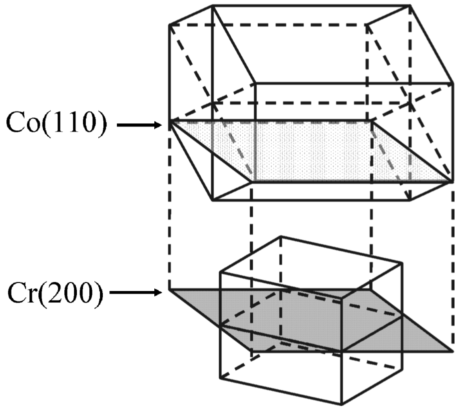

FIG. 2. Epitaxial growth of Co(110) planes on Cr(200) planes in longitudinal recording medium.

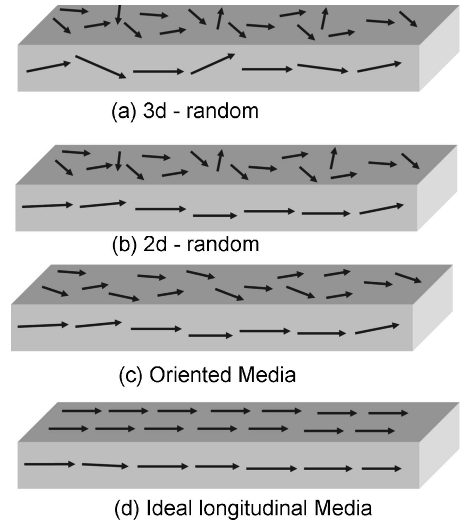

FIG. 3. The randomness of easy axis orientation: (a) three-dimensional (3D) random, (b) two-deminsional (2D) random, (c) oriented media, and (d) ideal orientation.

component of magnetization along the track direction can be enhanced, the SNR can be much larger than that predicted by Eq. (1), for the same number of grains. Several researchers have carried out research work along these lines. One way to minimize the randomness is to improve the number of grains that have an easy axis along the film plane. Several underlayers such as Cr, CrV, CrTi, CrMo, or combinations of these have been used by various researchers to improve the c-axis orientation parallel to the film plane.[31,32,37,42–46] When such underlayers are used, under suitable deposition conditions, the number of underlayer grains with a specific orientation can be enhanced. For example, if Cr or Cr alloys are deposited at about 250 °C, a Cr alloy can grow with a (200) texture. When Cr has a (200) texture, a Co alloy based recording layer can grow with a (110) texture, as shown in Fig. 2. Since the c axis is the easy axis of a Co crystal, the grains which have a (110) texture will have its magnetization parallel to the disk surface. Such grains with a (110) texture would have a larger component of magnetization parallel to the substrate than the grains whose easy axes are tilted away from the disk surface. Therefore, underlayers in the longitudinal recording media play a significant role in improving the performance of the recording media.

It has also been reported that the use of intermediate layers help to improve the easy axis orientation by improving the lattice matching between the Cr underlayers and the CoCrPt based magnetic layers.[47] Cr underlayers will have a lattice spacing of x nm. Co alloys with Pt would have a lattice spacing of y nm. The easy axis orientation parallel to the disk surface will improve if the difference between x and y is minimized. One way to improve the easy axis orientation is to use a suitable material such as a nonmagnetic CoCr alloy, which will have a lattice parameter which lies in between x and y. The introduction of an intermediate layer would also help in reducing the dead-layer effect in a Co alloy. If a Co-alloy layer is deposited directly on a Cr underlayer, there will be mixing at the interface. Therefore, a part of the magnetic layer adjacent to the underlayer would have a larger concentration of Cr. Such a larger concentration of Cr would reduce the M_s and K_u significantly and would make a part of the magnetic layer nonmagnetic, which is called a dead layer. Such dead-layer effects can also be minimized by adding a CoCr intermediate layer. It has even been reported that the introduction of a CoCr intermediate layer could improve the thermal stability of the media.[48]

C. Orientation ratio (easy axis orientation parallel to the track direction)

In addition to using an underlayer and an intermediate layer to improve the in-plane easy axis orientation, another way to minimize the randomness is to increase the number of grains that have an easy axis orientation parallel to the track direction. For the longitudinal recording media, such a partially ordered arrangement of easy axes was obtained as an unexpected consequence of the mechanical texturing process. The mechanical texturing process, which produces circular lines of a few tens of nanometers in width, was intended to avoid the stiction between the head and smooth disk. However, it was observed from the hysteresis loops of mechanically textured substrates that the recording media could show different coercivities (H_c) and remanent moments (M_r) when measured along the track or radial direction (along or in the transverse direction of the texture lines, respectively). The ratio of H_c in the circumferential direction to that in the radial direction was called orientation ratio (OR). During the initial days of such oriented media, it was not clear whether OR was beneficial or not.[49,50] Some simulation results pointed out that while OR may be beneficial at low densities, it could be detrimental at high densities.[51] However, further simulation and experimental works[52,53] carried out in the last five years indicate that OR could help improve the recording properties even at high densities. Recent experimental results have pointed out that the orientation ratio in the recording media arises because of the way in which the easy axes of Co is aligned. It has been reported that textured substrates induce a specific orientation of Cr along the direction of the textured lines. Such orientation helps to orient the easy axes of Co grains along the textured lines.[54]

Figure 3 illustrates the magnetization orientation for different media configurations. A recording medium in which the magnetic moments are randomly oriented with respect to the plane and with respect to the track [Fig. 3(a)] would have the lowest SNR. This is because, in such a recording medium, the component of magnetization that lies parallel to the disk surface or the track direction is low. This will lead to a reduction in the signal and an increase in the noise. However, the SNR can be increased by maximizing the number of grains that are oriented parallel to the disk surface [Fig. 3(b)]. This is typically achieved by the use of underlayers such as Cr, as discussed previously. Further increase of SNR can be obtained by orienting the magnetization of the grains along the track direction [Fig. 3(c)]. This is achieved by the texturing process, which can lead to an increased orientation ratio. Although the magnetization configuration, as shown in Fig. 3(d), is the ideal configuration for obtaining very high SNRs, it is not possible to achieve such orientations experimentally. Moving away from the configuration in Figs. 3(a)–3(d) is the way to increase SNR in longitudinal recording media.

D. Pulse width (PW_{50})

Theoretically, the linear density that can be supported by a recording medium is proportional to the pulse width (PW_{50}). PW_{50} is obtained by writing transitions (a sequence of 1s) at very low densities and measuring the width of the signal pulse at 50% height. PW_{50} of a longitudinal recording system is given by

$$PW_{50} = \sqrt{g^2 + 4(a+d)(a+d+\delta)}, \tag{2a}$$

where g is the gap length, d is the magnetic spacing, and a is the transition parameter, which is expressed as

$$a = \sqrt{4M_r\delta\left(d+\frac{\delta}{2}\right) \Big/ H_c}. \tag{2b}$$

In the above expression, M_r, δ, and H_c are the remanent moment, thickness, and coercivity of the medium, respectively. From the point of view of recording medium, PW_{50} is controlled mainly by transition parameter a, which is proportional to the $M_r\delta/H_c$. The initial advantages of thin film media over the particulate media were in the coercivity that can be tailored and in the higher value of $M_r\delta$ with thinner films that could produce a higher signal. However, as the areal density increased, research efforts were focused on reducing the $M_r\delta$ of the thin film medium while increasing the coercivity. Figure 4 shows the $M_r\delta$ and H_c of different products made for various generations of HDDs with different areal densities. While reducing the $M_r\delta$ and increasing the coercivity would theoretically reduce the value of a, in the real recording media, the transitions are often defined by the microstructure of the grains at the transition and the interaction between the grains. If the interactions are weak, the bit boundary will run through the grain boundary. This is because when the interactions are weak, every grain is expected to switch independently of each other and the bit boundary will be decided by the grain boundary [see Fig. 5(a)]. Therefore, if the grains are small, the bit boundary can be narrower.

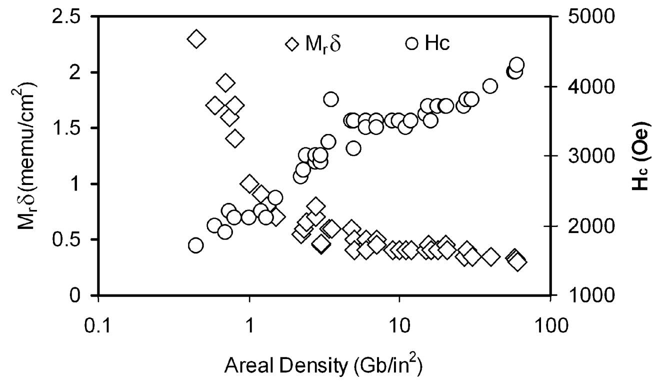

FIG. 4. Trend of M_rt and H_c as a function of areal density in longitudinal recording technology.

On the other hand, if the interactions are strong, the bit boundary will be much larger than the grain boundary. When the interactions are strong, a few grains may be coupled to each other and form a cluster. Therefore, in such a case, the bit boundary may be the cluster boundary. As the cluster boundary is broader than the grain boundary, the transitions will be broader [see Fig. 5(b)]. In the extreme case of a much stronger interaction, the switching mechanism itself could be different. In the earlier days of thin film media, the magnetization reversal mechanism was the domain wall motion. In this case, the domain wall formation determined the bit boundary and was much broader. Moreover, at high densities, two adjacent bits of a given bit could attract each other, causing the bit to vanish [Fig. 5(c)]. Therefore, in order to achieve a narrower bit boundary, it is essential to reduce the grain size and to reduce the exchange and/or magnetostatic interaction between the grains. Magnetostatic interaction is essentially determined by the $M_r\delta$. Reducing $M_r\delta$ to reduce magnetostatic interaction will also reduce the signal available from the transitions, as the signal is proportional to $M_r\delta$. To compensate for a reduction in $M_r\delta$, sensors have to be improved. Over a few generations, heads have moved on from inductive type to magnetoresistive (MR), giant magnetoresistive (GMR), and magnetic tunnel junctions (MTJs). From the recording media perspective, the improvement of the recording media is always focused on controlling exchange coupling, which will be described now.

E. Reducing exchange coupling between the grains

Some of the initial research work on the reduction of exchange coupling between the grains relied on the surface morphology of the underlayers. A rough surface was obtained by depositing very thick underlayers, which led to a physical separation between the magnetic layer grains.[55] When the grains were separated from each other, exchange coupling between the grains of the recording layer were reduced. However, having thick underlayers also led to a larger grain size in the recording layer. Therefore, better methods were needed to separate the magnetic layer grains from each other. Later, it was pointed out that exchange decoupling can be obtained by compositional segregation at high temperatures.[37] It is possible to sputter a recording medium that has two regions with different properties. The core of the

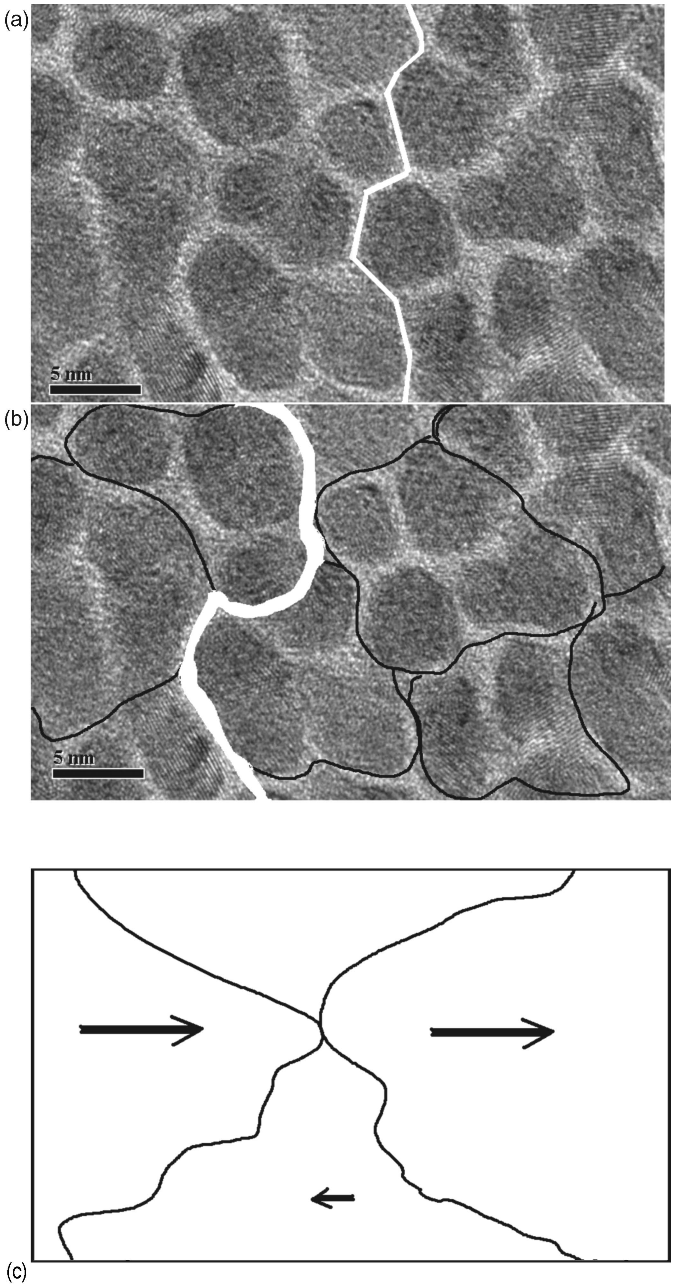

FIG. 5. Bit boundary in longitudinal recording for three cases: (a) decoupled grains with negligible exchange coupling, (b) magnetic clusters with moderate exchange coupling, and (c) domain wall motion reversal mechanism.

grain would have magnetic properties and the grain boundary would have nonmagnetic properties. Therefore, the nonmagnetic grain boundary would reduce the exchange coupling (Fig. 6). It was reported that additive elements such as Ta could enhance the grain boundary with nonmagnetic elements such as Cr, leading to better exchange decoupling.[56] Later, additive elements such as boron led to further improved grain isolation and much smaller grain sizes.[57] The current longitudinal recording media have a mean grain diameter of 7 nm, with well decoupled grains, which are expected to undergo switching independently of each other.

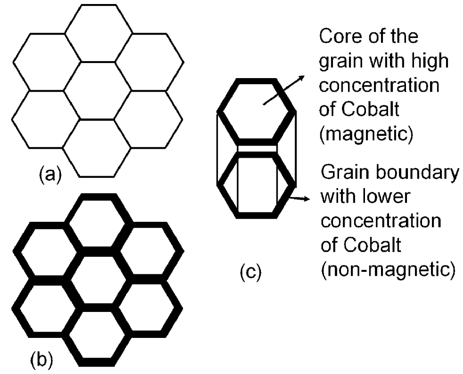

FIG. 6. Illustration of grains in magnetic recording media (a) with narrow grain boundary, (b) with broader nonmagnetic grain boundary, and (c) illustration of a grain with a magnetic core and nonmagnetic grain boundary.

III. CHALLENGES OF LONGITUDINAL MAGNETIC RECORDING

In magnetic recording, the energy barrier that prevents the magnetization of a particle from flipping is proportional to anisotropy energy K_uV, where K_u is the anisotropy constant of the material and V is the volume of the grain. It is this anisotropy energy that helps to store the bit and make HDD a nonvolatile storage device. Figure 7 shows the energy barrier of a magnetic particle. If the particle has to switch its magnetization from one direction to another, energy has to be supplied to overcome the energy barrier. An applied external field, which alters the energy barrier as in Fig. 7, is usually required to switch the direction of magnetization. In magnetic recording, this external field is applied using the write head, which is an electromagnet with nanometer scale gaps.

In the last section, it was discussed that the mean grain size and the $M_r\delta$ in longitudinal recording media need to be reduced to increase the areal density. A reduction of these two parameters leads to a reduction in the grain volume and, therefore, a reduction in the K_uV, if K_u is fixed. As K_uV of the grains get reduced, the energy barrier for magnetization reversal gets reduced. When the anisotropy energy K_uV gets lower, the thermal energy (k_BT) starts to compete with the anisotropy energy and makes the magnetization thermally excited and reversed. Such a phenomenon, where the magnetic particles could reverse their magnetization without any external field, is called superparamagnetism. Since a record-

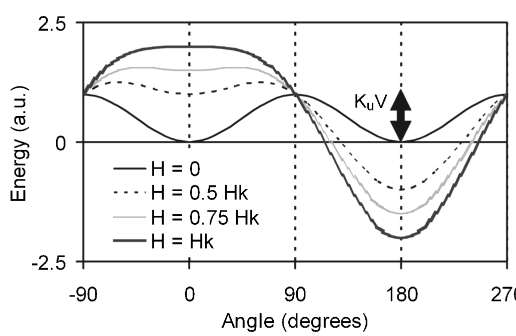

FIG. 7. The energy levels (for different applied fields) associated with a magnetic particle that switches coherently (as per the Stoner-Wohlfarth model).

ing medium is composed of grains with different sizes, some of the smaller grains would be more susceptible to thermal switching. Thermal effects have been investigated by several researchers for a long time.[58,59] Several methods have been reported to estimate the thermal stability factor, K_uV/k_BT.[58,60–67] It has been reported that the data will be lost even if 5% of the magnetization reverses due to thermal excitations. This superparamagnetic effect was considered as a serious threat to the areal density growth of longitudinal recording technology. Predictions pointed out that the areal density could not progress beyond 40 Gbits/in.^{2}.[68]

However, longitudinal recording technology pulled harder and crossed this limit in as early as 2000 with areal density demonstrations from several companies. In 2002, demonstrations of areal density higher than 100 Gbits/in.^{2} were reported.[53] Such a rapid progress even beyond the superparamagnetic limit occurred due to several reasons. The primary reason is the violation of the assumptions used in the prediction of areal density limit. Charap *et al.* assumed a bit-aspect ratio (BAR) (ratio of the track width to the bit length) of 16. However, the HDD industry chose to narrow down the tracks and increased the track density to increase the areal density. The 100 Gbits/in.^{2} demonstrations used a BAR of about 4. If the bit width is reduced and if the number of grains is also reduced, the signal will be reduced. However, reduction in the signal by reducing the BAR can be compensated by improvement in the read heads and improved media. For further discussion, only the improvements in the media are considered.

A. Oriented media

Oriented media is considered a key factor towards overcoming the superparamagnetic limit of 40 Gbits/in.^{2}.[50–53] While the simulation of Charap and Lu used isotropic media, later work on simulation and experimental studies pointed out that oriented media (OR$>$1) showed larger thermal stability than isotropic media.[52,53] It was also observed that in oriented media the magnetization was stable in the circumferential direction (desired direction) but unstable in the radial direction. Moreover, oriented media showed much lower noise than the isotropic media, for similar values of $M_r\delta$.[53] A sufficient discussion on the physics of oriented media has already been made in Sec. II C.

B. Antiferromagnetically coupled (AFC) media

Another reason for the success of longitudinal recording is the invention of antiferromagnetically coupled media (AFC) or synthetic ferromagnetic media.[33,69–77] In conventional recording media, the $M_r\delta$ reduction is achieved by a reduction in the thickness, which leads to a reduction in the K_uV. This leads to superparamagnetic effects. However, antiferromagnetically coupled media rely on two or more ferromagnetic layers which are antiferromagnetically coupled to each other, through the use of a thin Ru layer, as demonstrated in the pioneering work of Parkin *et al.*[78] The most common design had two antiferromagnetically coupled magnetic layers, out of which one (recording layer) is much thicker than the other (stabilizing layer). In such a design, $M_r\delta$ reduction is achieved by the partial cancellation of $M_r\delta$ of one layer by that of the other. In AFC media, because of the high concentration of Cr and B used in the recording layers, the antiferromagnetic coupling constant (J) observed was lower (about 0.08 erg/cm^2) than what was observed in pure Co/Ru/Co systems (about 5 erg/cm^2).[78] In a simple energy model, to observe antiferromagnetic coupling at remanence, the antiferromagnetic coupling energy has to be greater than the anisotropy energy of the bottom layer grain (K_uV).[74,79] However, with a J of 0.08 erg/cm^2, it is not possible to observe antiferromagnetic coupling and the $M_r\delta$ cannot be reduced. Piramanayagam and co-workers have reported that the thermal energy helps to reduce the energy barrier of the bottom layer grain in AFC media.[75,77,80] Therefore, antiferromagnetic coupling can be observed even for smaller values of J (0.08 erg/cm^2) than needed (about 1–2 erg/cm^2) in the absence of thermal energy. AFC media are considered as an interesting design, which made use of thermal energy to overcome the problem of thermal energy. Although there are several theories and explanations proposed to explain the thermal stability of AFC media, in simple terms, the thickness of the recording layers could be larger than that in the conventional design and thermal stability could be obtained.[81] As a summary, it can be mentioned that the improvements in oriented media and AFC media and the combination of these two have made a significant contribution in increasing the areal density of longitudinal media from a recording media perspective. It is essential to note that the improvements in the head and other components and design of the system are also important.

The thermal stability issue of longitudinal recording technology is the physical limit that enhanced the current interest in perpendicular recording. However, the bottleneck for longitudinal recording technology is still based on the available write head materials to write information. It is, indeed, possible to make longitudinal recording media that can provide thermal stability at higher areal densities than the present densities. However, writing and reading information from such a medium is the challenge.

IV. HISTORY OF PERPENDICULAR RECORDING

Demagnetizing fields are experienced in any ferromagnetic or ferrimagnetic system and are expressed as

$$H_d = -NM, \tag{3}$$

where N is the demagnetization tensor and M is the magnetization vector. N depends on the shape and direction of the magnet. The rule of thumb is that the demagnetization field is stronger when the magnetic charges or the magnetic poles are nearer. In longitudinal recording, as the linear density increases, the distance between the magnetic charges or the magnetic poles decreases [Figs. 8(a)–8(c)]. This leads to an increased demagnetizing field. In 1975, Iwasaki and Takemura experimentally observed that circular magnetization would be formed in a longitudinal recording technology because of demagnetizing field if thicker films were used.[1] Such circular magnetization would not be able to produce high output voltage at high linear densities. They predicted

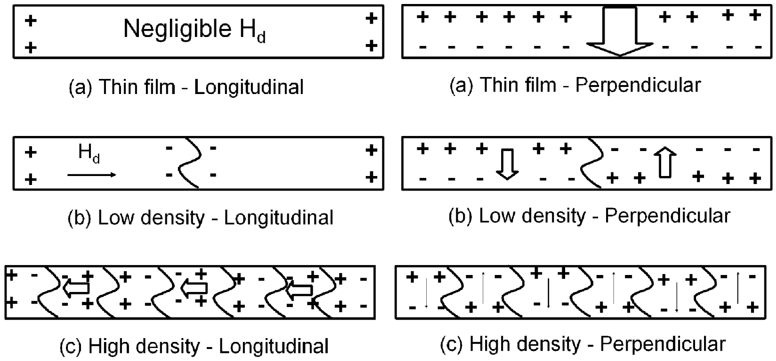

FIG. 8. Illustration of magnetic charges and the associated demagnetizing fields for longitudinal and perpendicular recording (a) thin film, (b) low density, and (c) high density. The arrows indicate the direction of demagnetizing field. Block arrows are used to show the higher strength of demagnetizing field.

and proposed that in perpendicular recording technology, the demagnetization field would be reduced at high linear densities. Therefore, perpendicular recording is a superior technique to achieve high linear densities [see Figs. 8(a)–8(c)]. This section will describe the initial research works on perpendicular recording since 1975.

Since their first proposal in 1975, the team from Tohoku University came up with many other inventions from 1975 to 1980.[1–3,24] These inventions were crucial in illustrating the significance of the perpendicular recording technology and were also the foundation for some of the current developments. Media based on CoCr alloys with a perpendicular anisotropy, double-layered perpendicular recording media with a CoCr recording layer and NiFe as the soft underlayer, and design of several types of heads for perpendicular recording were developed. Iwasaki and Nakamura developed a perpendicular recording medium based on CoCr and demonstrated that 30 kbits/in. could be achieved with 1000 nm thick recording layer. This linear density was significantly larger than that can be supported by longitudinal recording then.[26]

Although the team of Iwasaki and Nakamura have proposed several configurations for perpendicular recording, the invention of double-layered perpendicular recording medium and the single-pole head design are crucial for the superiority of perpendicular recording over longitudinal recording. Together, these inventions provide superior writing performance in perpendicular recording than is possible in longitudinal recording. Figure 9 illustrates the writing process in longitudinal and perpendicular recording. In longitudinal recording, if the fringing field from the head is higher than that of the coercivity of the grain, the magnetization will be reversed and writing will be achieved. In the recording medium, the grains have different energy barriers because of the distribution in the size and anisotropy constant. Therefore, in order to reverse all the grains at smaller time scales encountered in hard disk recording, the field from the head is made to be two to three times the coercivity of the material (field required to reverse 50% of the magnetization). However, if a comparison is made between the fringing field and the field at the gap, the fringing field is less than the field available at the gaps by about 50%. In longitudinal recording, the weaker field is used to write the information. In perpendicular recording technology, the gap field is used for writing the information. This is achieved by the use of a soft underlayer and a single-pole head. The single pole head, the recording media, and the SUL are illustrated in Fig. 9(b). SUL, being highly permeable, can act as a magnetic mirror. It can be visualized that in perpendicular recording the media is virtually placed in the gaps of the poles and hence under higher writing fields. Detailed information about the writing and reading process of perpendicular recording can be obtained from the recent reviews by Litvinov and Khizroev.[29,30,82]

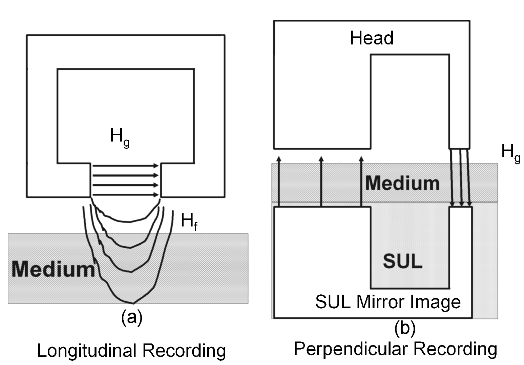

FIG. 9. Writing process in (a) longitudinal and (b) perpendicular recording. In perpendicular recording technology, the medium is virtually placed in the pole gaps between the head and the mirror image in SUL.

Research on perpendicular magnetic recording media based on CoCr continued after the invention of Iwasaki *et al.* Watanabe *et al.* proposed CoCrNb as the recording medium. CoCrNb was expected to form an initial layer with an in-plane growth layer to act as an image plane, similar to the one formed by a SUL.[83] Iwasaki *et al.* have studied the effect of impurity gases on the properties of CoCr perpendicular recording media and pointed out that the addition of nitrogen could deteriorate the perpendicular anisotropy drastically.[84] Honda *et al.* have studied the deposition of CoCr films with a perpendicular anisotropy by a low temperature deposition process.[85] The concept of using high pressure was similar to that used in the longitudinal recording media in the early 1990s.[55] Honda *et al.* have also studied CoCrNb as the perpendicular recording media.[86] Futamoto and co-workers have studied CoCr, CoCrPt, and CoCrTa based recording layers.[4,6,7] In parallel, alternative materials based on barium or strontium ferrites were also considered for perpendicular recording.[87–89] In addition to CoCr alloys and ferrites, Co/Pd multilayers were also considered for perpendicular media.[90–93] Several investigations were also undertaken to study the noise of the soft underlayers and to minimize the noise by the choice of materials, etc.[94]

In spite of several advantages that the perpendicular recording had over the longitudinal recording technology, the perpendicular recording was not given a serious thought until this century. The areal density demonstrations on perpendicular recording media were lagging behind that of longitudinal recording. Cain *et al.* summarized several challenges associated with the practical implementation of perpendicular recording in 1996.[95] In 1997, Thomson challenged the perpendicular magnetic recording community to come up with areal density demonstrations of 200 Gbits/in.^{2} by 2002.[96] As far as the perpendicular recording medium itself is concerned, it had many problems which made it inferior to that of longitudinal recording. For example, in 2001, the recording medium for longitudinal recording had a grain size of about 8–9 nm, which was significantly smaller than the possible grain size in perpendicular recording (about 12 nm). The perpendicular recording media studied in the early 2000s had higher compositions of Cr in order to obtain the desired grain boundary segregation. However, the presence of more Cr also led to a reduction in the anisotropy constant of the grains. If the anisotropy constant is not high in perpendicular recording, some grains may undergo thermally assisted switching. Such grains will be a source of dc noise.

In addition, the soft underlayer issues were also not solved, which led to an inferior performance of perpendicular recording. Compared to the areal density demonstration of 50 Gbits/in.^{2} by perpendicular recording technology in 2000, longitudinal recording technology had demonstrated 100 Gbits/in.^{2}. However, moving beyond 100 Gbits/in.^{2}. turned out to be the last mile of marathon for longitudinal recording. No areal density demonstration was made beyond the 130 Gbits/in.^{2} areal density.[53] Even though the antiferromagnetically coupled media could provide the needed thermal stability at very low $M_r\delta$ values, significant improvements in the head sensitivity to read signal from such low $M_r\delta$ media were not made.[97]

V. CURRENT PERPENDICULAR RECORDING MEDIA

For the past five years or so, significant improvements were made in the perpendicular recording. The improvements came from the recording layer and soft underlayers of the recording media, and also the writing heads, which made perpendicular recording technology more promising.[13,15,21,98–100] In 2003, an areal density demonstration of 174 Gbits/in.^{2} was achieved using perpendicular recording technology. Although the current products have an areal density of about 130 Gbits/in.^{2}, laboratory demonstration of over 340 Gbits/in.^{2} has been reported, indicating the potential of perpendicular recording.[101] In this section, the progress made in the field of recording layers, intermediate layers, and soft underlayers in the past few years will be discussed. In Sec. V A, the various layers of perpendicular recording media and their functions will be discussed. In Secs. V B to V D, the research progress made in soft underlayers, intermediate layers and recording layers of perpendicular recording media will be described. Section V E will cover some of the latest work.

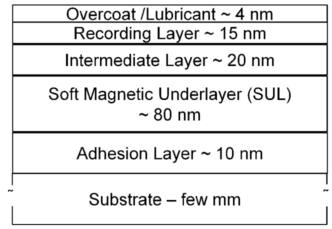

FIG. 10. Different functional layers of perpendicular recording medium with approximate thickness (layers are not to scale).

A. Description of various layers and their functions

Figure 10 shows various functional layers, such as the soft underlayer, recording layer, etc., of a typical double-layered perpendicular recording medium. In the practical designs, there may be more than one layer involved for every function. The most advanced or exploratory designs may have a totally different structure than described. However, only a simple design is shown, and for the sake of simplicity, only one layer is shown to illustrate the function of each layer. For example, the soft underlayer itself may be composed of many layers or it may be an antiferromagnetically coupled soft underlayer.[13] Similarly, the intermediate layer itself may consist of many layers, including a seed layer.[102–105] However, this picture is tentatively sufficient to understand the functions of the different layers in the perpendicular recording medium.

The recording medium may be coated on an AlMg alloy precoated with a NiP layer or a glass substrate of a dimension suitable for its particular application. At this point of time, server and desktop HDDs have disk substrates with an outer diameter (o.d.) of 95 mm. HDDs for laptops have disks with an o.d. of 65 mm, and other form factors such as 1.8 and 1 in. are also common in consumer electronics applications such as MP3 players, etc. HDDs with 1.3 in. disks are also being considered to compete with the flash drives in the CE market. Most of the layers in a hard disk medium are deposited by the sputtering process. Prior to the deposition of any layer, the substrates are cleaned to remove chemical and particle contaminants. Then, the substrate is first coated with an adhesion layer or an interface layer, made of Ta, Ti, or an alloy of these materials. This layer helps in improving the adhesion of SUL and all the other layers with the substrate. The next layer deposited is a soft magnetic underlayer. As discussed before, the soft magnetic underlayer helps in conducting the flux from the writing pole of the head to the trailing pole. On top of the SUL, some intermediate layers may be deposited with or without seed layers. The intermediate layers have at least two functions in the perpendicular recording layer. Exchange-decoupling the SUL and the magnetic layer is one of them.[106] If the SUL and the recording layers are coupled, the recording medium may show a larger noise. Another function of the intermediate layer is to provide epitaxial growth conditions for the recording layer. For perpendicular media with Co-based recording layers, it is essential to obtain grains with a Co[0002] orientation perpendicular to the film plane. Therefore, the intermediate layer should have the fcc(111) or hcp(002) texture.[104,107] Usually, a seed layer is deposited below the intermediate layer to enhance a preferred growth. The recording layer is a Co-based HCP alloy for most of the designs carried out so far. The function of the recording layer is to store information for long periods of time (about 10 years) and to produce the signal when reading the information back. The disk will also be coated with carbon overcoats and lubricants to prevent the disk from failures caused by chemical reactions or mechanical impacts.

B. Soft magnetic underlayers

As discussed before, the soft magnetic underlayer in the perpendicular recording media is helpful during the writing of information. It is the presence of a soft magnetic underlayer (in the recording media) that provides a significant advantage for perpendicular recording technology. With a soft magnetic underlayer and a single-pole head, higher writing fields can be achieved. If higher writing fields are achieved, materials with high K_u can be used as the recording media. Therefore, smaller grains can be used in the recording medium to store information. With smaller and stable grains, higher linear density could be achieved. Thus, soft magnetic underlayer is a significant part of perpendicular recording technology. The fact that the longitudinal media did not require a soft magnetic underlayer created a handful of new challenges in perpendicular recording, which are described in this section.

1. Manufacturing issues

During the fabrication of a recording medium, all the layers discussed in the previous subsection (except the lubricant) are deposited by a sputtering process. The disk substrate will pass from one sputtering chamber to another and finally leave the deposition system. During this process, each layer will be sputtered in a sputtering chamber that is isolated from the rest of the chambers. The number of disks that can be produced by a system in 1 h (throughput) depends on the time that each disk spends in a particular chamber. The deposition of thicker layers needs longer time to sputter, which would reduce the throughput. It has to be noted that the thickness of SUL alone could equal the total thickness of longitudinal media. Another manufacturing problem that would arise because of thicker SULs is that higher deposition rates would be needed, which are usually achieved at higher powers. However, sputtering at higher power would cause spitting of particles, which would deteriorate the surface of the disk and make it unsuitable for the flying heads in a hard disk drive. Therefore, thicker layers are not desirable in the production. In order to avoid the above-mentioned problems, thicker layers are usually deposited in two or three chambers to increase the throughput. This leads to an increase in the number of sputtering stations, which will lead to a significant investment. However, if the performance of perpendicular recording media is significantly higher, investment will not be of concern. This was one reason why the industry did not choose perpendicular recording technology for a long time, as the longitudinal recording media provided significant performance and cost advantages.

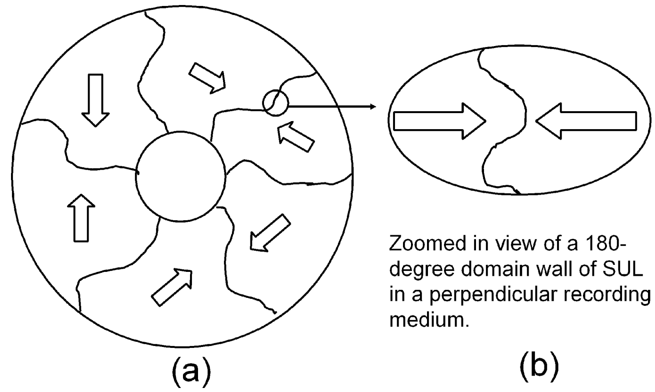

FIG. 11. Illustration of 180° domain formation in SUL and an enlarged view of a transition.

2. Noise of SUL

The fact that the SUL is too thick compared to the recording layer and is also made of materials with a larger magnetization than that of the recording layer also leads to the problem of noise from the SUL. As early as 1984, it has been reported that the presence of SUL, such as Permalloy, can increase the noise from the formation of domains.[108] Uesaka *et al.* have studied Co–Mo–Zr amorphous underlayers and reported that three kinds of noises, viz., spike noise, medium noise, and low noise, have been observed.[94] They have indicated that the spike noise arises due to the domain walls of the soft magnetic underlayer. The medium noise, which arises because of the interaction between the SUL and the residual magnetization of the head, was weaker than the spike noise but larger than the low noise.

In the absence of a field, a soft underlayer may form domains, such as stripe domains or 180° domains, as these are ways to minimize the magnetostatic energy. However, the formation of such domain walls would also generate strong magnetic fields, which will cause strong noise during the reading process. A 180° domain wall with the magnetization along the track direction can be considered similar to a transition in longitudinal recording. In longitudinal recording, the signal produced by such a transition will be proportional to its $M_r\delta$. Therefore, if a thick SUL forms a 180° domain wall, the signal produced will be very high. Figure 11 illustrates such a situation. For example, let us consider the soft magnetic underlayer materials used currently for recording, which have a saturation magnetization of about $1200\ \text{emu/cm}^3$. If the squareness of the as-deposited single layer is 0.1, the remanent magnetization is $120\ \text{emu/cm}^3$. If the thickness of the soft underlayer is 100 nm, then the $M_r\delta$ will be $1.2\ \text{memu/cm}^2$ (In comparison, the $M_r\delta$ of longitudinal and perpendicular recording media are about 0.4 and $0.7\ \text{memu/cm}^2$). Therefore, a 180° domain wall of such a SUL will produce a signal (rather, it should be called noise, since SUL is not supposed to produce any signal during the reading) much stronger than that of longitudinal or perpendicular recording media. Therefore, the noise from the soft underlayer is a serious concern. If the domain walls formed in the SUL are fixed in one position, it would be possible to mark that position of the hard disk drive as a bad sector and still use perpendicular recording. However, the domains that

TABLE I. Properties of some soft magnetic materials.

Material	H_k (Oe)	B_s (T)	μ	Remarks
CoTaZr	20	1.4	600	Amorphous material. Exhibit low noise property. Commonly used in the perpendicular media products.
CoNbZr	12.5	1.2	500	Amorphous material. Used occasionally as SUL.
CoNiZr	25	1.2	⋯	Not commonly used.
$Fe_{44}Co_{44}Zr_7B_4Cu$	⋯	2	⋯	Nanocrystalline. Considered for future perpendicular media based on FePt.
$Ni_{81}Fe_{19}$	5	1	2000	Crystalline with a fcc structure.
$Fe_{65}Co_{35}$	100	2.4		bcc structure. Considered for future perpendicular media based on FePt.
$Ni_{45}Fe_{55}$	50	1.6		
FeAlN	15	2		
$(Fe_{70}Co_{30})N$	20	2.4	1000	
FeAlSi	⋯	1.6	250	bcc structure—nanocrystalline.
FeTaC	⋯	1.7	200	bcc structure—nanocrystalline.

cause the spike noise may move from one place to another, as pointed out by Kikukawa *et al.*[109] Therefore, domain walls are a serious concern. Even though the stripe domains are not as severe as the 180° domains, stripe domains also cause noise during the reading. Litvinov *et al.* have reported that when the stripe domains were swept away by using external magnets during the reading process, the noise was much lower and the signal was higher.[28]

Since the pioneering work of Desserre and Uesaka *et al.*, several attempts have been made to understand more about spike noise and to find out ways to minimize the noise arising from the SUL. One approach is to use new materials that could probably show fewer domains and hence a lower spike noise. Another approach is to do laminations of SUL material to minimize the domain formation. A third approach is to combine new materials, laminations, and/or processes. On the material front, several materials such as CoTaZr, CoNbZr, FeAlSi, NiFeNb, FeTaC, FeTaC(N), CoFeB, FeAlN, etc., have been attempted.[8,11,12,15,18,110,111] In addition to solving the problem of noise, searching a suitable soft underlayer material would also help in meeting several requirements of a SUL, as reported by Litvinov *et al.*[28] Table I summarizes the properties of selected SUL materials.

Sato *et al.* have investigated the noise of NiFe underlayers (of different compositions) with various thicknesses and permeabilities.[112] They have pointed out that the noise behavior depends on the permeability, which affects the domain structure. $Ni_{90}Fe_{10}$ films with a permeability of 200 showed stripe domains with a wall pitch of several microns. $Ni_{82}Fe_{18}$ films with a permeability of 2000 showed no stripe domains. However, they showed 180° domains with a wall pitch of several tenths of a millimeter. It was also pointed out that the spike noise was more for films with a high permeability. Uesaka *et al.* have also observed a similar result that with a decrease of permeability or increase of coercivity, the noise of SUL decreases.[94] In the paper of Otomo, discussion has been made on Co–*TM*–Zr amorphous sputtered films, where *TM*=Nb, Ta, Mo, W, and Ni. Although they have not studied these films for applications as SULs, the results presented there are useful in the SUL design.[113] Honda *et al.* have studied different types of SULs, such as *a*-CoTaZr, *a*-CoNbZr, FeTaC, and FeAlSi, and have compared the performance using analytical magnetic force microscopy.[8] It was observed that the medium with the Co–Ta–Zr underlayer shows a low medium noise and high resolution characteristics at high recording densities. It is to be noted that, in the current state-of-the-art perpendicular hard disk media research and production, CoTaZr is one of the candidate materials for SUL. Typical concentrations of Ta and Zr in the Co alloy are about 6–12 and 2–6 at. %, respectively.

The second approach that has been used to solve the problem of the SUL noise is to use lamination. Hikosaka *et al.* have investigated FeAlSi/C multilayers and have observed a reduction in atomic force microscopy (AFM) roughness and the noise.[114] The reduction of roughness was attributed to a reduction in the grain growth. No significant reduction in the coercivity was observed because of lamination. Soo *et al.* have studied FeCo/C multilayers and have observed reduced coercivity with lamination.[115] Tanahashi *et al.* have studied laminated FeTaC SULs with a Ta layer.[116] Laminated SULs were found to have low coercivities due to the magnetostatic interaction between adjacent magnetic layers. The medium with a laminated SUL also showed much lower spike noise than the medium with a single-layer SUL. The other approaches to reduce the noise of SUL have been to use other processes such as electroplating, biased sputtering, etc. In addition to reducing the noise, electroplating

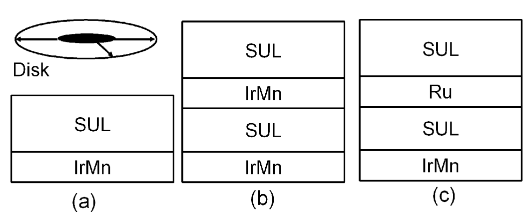

FIG. 12. Schematic view of different ways in which the SUL can be exchange biased in the radial direction as described in (a) Ref. 119, (b) Ref. 16, and (c) Ref. 121.

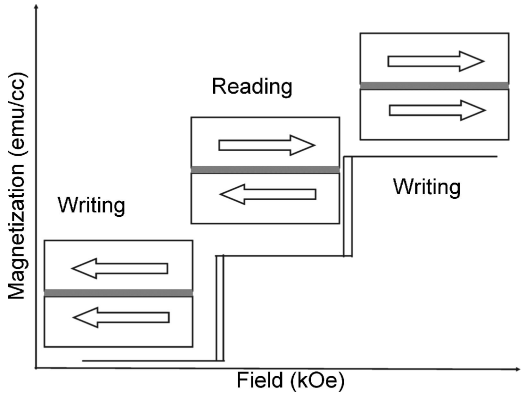

FIG. 13. Magnetization of two layers of antiferromagnetically coupled SUL during the writing and reading (remanence).

would also help to reduce the cost associated with a sputtering process.[117,118] However, the idea of electroplating the soft underlayer has not been taken up by the media companies because attaining radial anisotropy and antiferromagnetic coupled layer structures (to be discussed later) in plated SUL are challenges.

In addition to the research on materials and lamination of SUL, several effective advances have been made in the SUL design in the last ten years. One of the designs proposed to overcome the issue of noise is the use of pinned layers.[119,120] In this design, an in-plane hard magnetic layer such as SmCo, the SUL (CoZrNb), and the recording layer were deposited sequentially and were later annealed in the presence of a radial magnetic field. The presence of the magnetic field induces a radial anisotropy in the SmCo layer and SUL. It was observed that the disks with SmCo layer showed a lower noise due to reduced domain formation in the SUL because of the pinning effect. Such kind of pinning of the SUL can also be achieved by using antiferromagnetic layers. Several researchers have investigated the performance of SULs deposited with antiferromagnetic layers, such as IrMn, FeMn, and NiMn.[16,116,121] In this SUL design, the antiferromagnetic layer orients the soft magnetic underlayer in the radial direction (Fig. 12). It was also reported that the spike noise was completely eliminated with IrMn underlayers. It was also found that the total noise generated from the SUL was reduced as the exchange bias field increased. On the other hand, the writability was deteriorated when the exchange bias field increased. In addition, in order to use the antiferromagnetic layers, heat treatment in the presence of magnetic field is necessary.

An easier alternative to reduce the noise of soft magnetic underlayers is to use antiparallelly coupled soft underlayers (APC SUL) through a thin Ru layer, similar to the concept used in the antiferromagnetically coupled media discussed in Sec. III.[70–83] In this case, two or more soft magnetic underlayers could be made to couple to each other antiferromagnetically during the reading, and theoretically the remanances of each layer should cancel each other, as in Fig. 13.[13] However, during the writing process, the Zeeman energy would overcome the antiferromagnetic coupling energy.[79] Therefore, the two layers are aligned in the same direction and would produce a high field during writing. Such an antiferromagnetic coupling has been reported to reduce the noise of the SUL.[13] Figure 14 shows the track average amplitude (TAA) voltage of conventional CoTaZr SULs and the APC SULs, as measured by Acharya *et al.*[13] It can be noticed that the simple CoTaZr SULs produce a larger TAA (spike noise) at certain disk positions and APC SULs produce a very low TAA throughout the disk. Therefore, it is clear that APC SULs would help to reduce the noise. Acharya *et al.* have reported higher SNR for perpendicular media with APC SULs than for media with conventional SULs.[13] It has also been reported that the APC SULs also help to reduce the adjacent track erasure (ATE), which is another type of problem associated with SUL. Antiparallelly coupled SUL with antiferromagnetic underlayers have also been investigated. Tanahashi *et al.* have compared the conventional SUL with APC SUL and with antiferromagnetically pinned APC SUL.[121] While the conventional SUL shows closure domains in the Kerr images and spike noise, the pinned APC SULs did not show any domains and spike noise. However, the

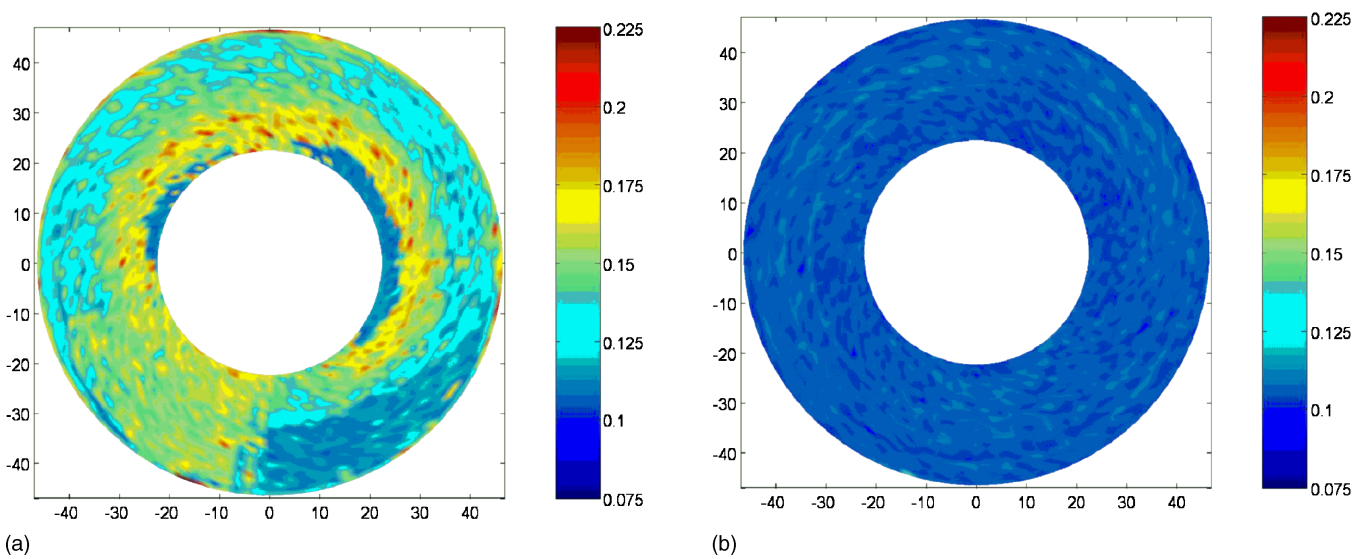

FIG. 14. (Color online) Mapping of noise pattern of SUL with a spin-stand and a read-write head: (a) single SUL and (b) antiparallelly coupled SUL.

APC SUL showed a multidomain structure but no remarkable spike noise. Both the APC SUL and the pinned APC SUL showed a very low ATE as compared to the single SUL. At this point of time, the pinned APC SUL did not seem to show any significant advantage in terms of performance over the APC SUL. Therefore, most likely, APC SULs will be used in the first-generation perpendicular recording media. For future recording media, where significant noise reduction is desired, pinned APC SULs may be used. It has to be noted that the radial alignment of easy axis of SUL will be beneficial in reducing the noise from SUL. The radial alignment reduces the component of M_r of the SUL in the circumferential direction and hence reduces the noise. Typically, the radial alignment can be obtained by deposition in the presence of a radial magnetic field or by carrying out annealing in the presence of a radial magnetic field. Modern sputtering machines are equipped with such features.

3. Choice of materials and other design issues

Besides producing a low noise during reading, the SUL must also be designed to improve the writability, enhance the read-back signal, and reduce the ATE. Litvinov *et al.* have covered several design aspects of SUL related to writability and read-back signal.[28] According to them, the saturation magnetization of SUL should be chosen in such a way that the following relation is satisfied:

$$4\pi M_s(\mathrm{SUL}) \times A(\mathrm{SUL}) = 4\pi M_s(\mathrm{PT}) \times A(\mathrm{PT}). \qquad (4)$$

Here, SUL refers to the soft underlayer, A refers to the area, and PT refers to the pole tip. If the SUL has a lower value of M_s, as compared to that of the writing pole, there will be deterioration in the trailing field gradient. A comparison of NiFe ($4\pi M_s$=1 T) and FeAlN ($4\pi M_s$=2 T) indicated that the NiFe produced a wider trailing field. In addition to a proper choice of SUL material with a suitable M_s, the thickness of SUL also has to be carefully studied. If the SUL is too thin, it will lead to poorer writing and read-back signal (RBS). RBS was also shown to be related to the K_u of the SUL material used. A comparison of the RBS from identical Co/Pd media deposited on $Ni_{80}Fe_{20}$, $Ni_{45}Fe_{55}$, and FeAlN indicated that the RBS depends on the K_u of the SUL material used. Litvinov *et al.* explained this result based on the domain wall width. Since the domain wall width is inversely proportional to the K_u, $Ni_{80}Fe_{20}$ (with a H_k of 5 Oe) would have a larger domain wall width as compared to that of $Ni_{45}Fe_{55}$ (H_k of 50 Oe). Such a domain wall will reduce the imaging ability of the SUL, leading to accelerated roll-off curves. Xiao *et al.* have recently proposed that the critical thickness of the SUL (t_{sul}) can be thinner than that proposed by Litvinov *et al.* Xiao *et al.* assumed the flux conduction in both cross-track and down-track directions and calculated that $t_{\mathrm{sul}} > [M_s(\mathrm{PT})TW]/[2M_s(\mathrm{SUL})(T+W)]$, where T and W represent the thickness and width of the poles.[19] These results indicate that at high track densities t_{sul} will be thinner. It is also useful to mention that the t_{sul} will be even smaller if shielded pole designs are used.[13]

4. Erasure issues

Besides the issue of the production and noise of SUL, the serious challenge posed by the SUL was the erasure problems associated with the combination of single pole head (SPH) and the SUL. Cain *et al.* have reported that the plated Permalloy soft underlayer acts as a flux antenna, channeling the magnetic flux from the spindle motor and actuator into the head.[95] They have reported that a stray field as low as 3 Oe is harmful for the drive.

According to Cain *et al.*, the field B in the write gap is given by the expression

$$B = \mu H\left(\frac{A_0}{A_{g1}}\right)\left(\frac{R_{b2}+R_{g2}}{R_{b1}+R_{g1}+R_{b2}+R_{g2}}\right), \qquad (5)$$

where R represents the reluctances and A represents the area of the heads. The field in the write gap is proportional to the stray field through the permeability of the head μ. Therefore, if the permeability of the head is improved, the stray field sensitivity becomes stronger. The term A_0/A_{g1} indicates that the stray field induced at the write gap increases as the area of the pole decreases, which indicates the seriousness of the problem at high densities. The four reluctances in the denominator of the third term indicate that the induced field at the write gap increases as the total reluctance of the circuit is reduced. In summary, as the circuit is made more efficient, stray field sensitivity increases. The problem described above could be avoided by using different types of head structures.[22,23]

In recent perpendicular recording technology, the shielded pole head design may involve an additional shield next to the write pole in order to increase the write pole gradient. However, the shield may lead to an additional flux path that consists of pole shield, SUL, and the reader shields. Therefore, during writing, the write coil also induces flux through this additional path, which leads to adjacent track erasure. Since the shields have a larger foot print, the erasure can occur over a wide area. Therefore, such an erasure is called wide area adjacent track erasure (WATER) or ATE. Acharya *et al.* have pointed out that the ATE was suppressed in antiparallel coupled SULs (APS) and the reduced permeability of APC SUL was suggested as the reason.[13] Zhou *et al.* have carried that study further and have pointed out that the permeability of the top surface of the SUL was responsible for reducing ATE. They proved this by making a series of samples such as an APC SUL , an APC SUL with enhanced antiferromagnetic coupling, and a double layered APC SUL . It was observed that the ATE was proportional to the permeability.[122]

C. Intermediate layers (IL)

As discussed before, the intermediate layers have different functions, such as exchange breaking and inducing a textured growth in the recording layer. The progress in this area is reviewed in this section.

1. Exchange breaking

When a magnetically soft layer and a hard layer are next to each other, the properties of both the layers would change

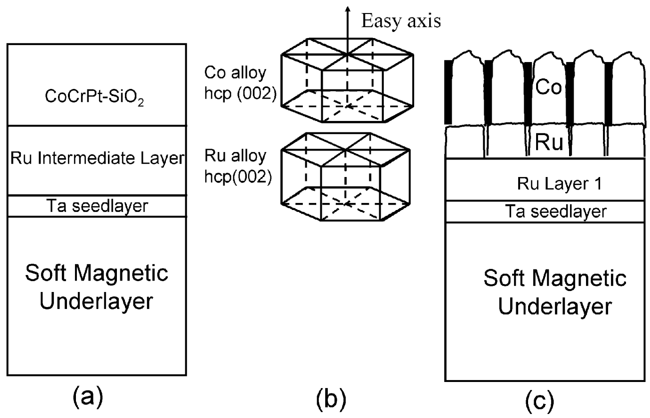

FIG. 15. Illustration of (a) typical layers of current perpendicular recording media, (b) heteroepitaxial growth, and (c) design that involves dual Ru layers.

because of the exchange interaction. Such an exchange interaction could reduce the coercivity of the recording layer and produce a larger noise during the read-out and so on. Honda *et al.* have used magnetic force microscopy (MFM) to observe the interaction between a CoTaZr SUL and the CoCrPt recording layer.[106] A strong magnetic interaction was observed when the layers were in direct contact with each other. On the other hand, when a thin $Ti_{90}Cr_{10}$ layer was introduced (5–10 nm), the interaction was found to diminish (from MFM) and a reduction in the noise was observed. It was suggested that optimization of the intermediate layer thickness and the noise of the SUL are crucial to the development of perpendicular recording media. Das *et al.* have investigated the interaction between NiFe SUL and CoCrPt recording layer by using ferromagnetic Hall effect measurements.[123] They have also reported that interaction is present for the samples with no intermediate layer.

2. Perpendicular C-axis orientation

Another function of intermediate layers is to induce a perpendicular hcp[00.2] orientation for the Co-alloy-based recording layer. In Co-alloy-based perpendicular recording media, the easy axis (c axis of the hcp crystal) needs to be deposited with a perpendicular orientation with respect to the substrate [Fig. 15(b)]. When measured with XRD, it will be seen as hcp(00.2) peaks in the θ-2θ scans at about 44°, depending on the constituents of the Co alloy. For Co alloys with Pt as an additive element, hcp(00.2) peaks will be seen at around 43° because the addition of Pt will lead to an expansion of the c parameter. In the current design of perpendicular recording media, amorphous materials such as CoTaZr or FeCoB are considered as the SUL because they could provide a lower noise. Moreover, the amorphous SULs also exhibit a very low average roughness (closer to that of the substrate) of about 0.15 nm. When a Co alloy is deposited directly on top of the a-SUL, the hcp(00.2) texture would not develop with a low dispersion. Therefore, it is essential to grow intermediate layers that would induce a hcp(00.2) orientation on the Co-alloy-based recording layer.

Several research works have been published since the 1980s. Table II summarizes some of the earlier works on perpendicular recording media. Most of the papers before 2002 were based on CoCrPt or CoCrPtB and were deposited at high temperatures.[6–10,15,126] However, the present day media based on CoCrPt-oxide (to be discussed in the next section) are deposited at room temperature, and they need the presence of different kinds of seed layers and intermediate layers than considered before (Table II). The intermediate layers for CoCrPt-oxide based media will be discussed henceforth. The initial publications of oxide based media appeared in 1994. However, the study by Hikosaka did not indicate the use of any intermediate layers,[127] while in the

TABLE II. List of intermediate layers (ILs) in the earlier days of perpendicular recording.

Reference	Intermediate layer	Recording layer	SUL	Remarks
Futamoto *et al.* (Ref. 4)	Sc, Ti, Y, Re, Ru, Ge, etc.	CoCr layer by e-beam.	⋯	$\Delta\theta_{50}$ of 5° with Ge.
Ando and Nishihara (Ref. 120)	⋯	CoCrTa (30–100 nm thick)	CoNbZr	$\Delta\theta_{50}$ of 2.5°–3.5°
Ariake *et al.* (Ref. 11)	Ti, CoNbZr	CoCrPtNb	NiFeNb	No improvements in texture with IL.
Hirayama *et al.* (Refs. 124 and 125)	$TiCr_{10}$, CoRuCr, and $TiCr_{10}$/CoCr	CoCrPt	⋯	Low noise with TiCr layers.
Hirayama *et al.* (Ref. 126)	TiCr (30 nm)	CoCrPt (100 nm)	⋯	$\Delta\theta_{50}$ of 2.3°, H_c=1600 Oe, S=0.48
	$CoCr_{35}$(20 nm)/TiCr(30 nm)	CoCrPt (33×3 nm)	⋯	$\Delta\theta_{50}$ of 2.4°, H_c=3350 Oe, S=0.85
Uwazumi *et al.* (Ref. 10)	CrTi	CoCrPt(Ta,B)	⋯	⋯
Roy *et al.* (Ref. 91)	Ta, ITO	Co/Pd	⋯	Ta induces ⟨111⟩ texture with a $\Delta\theta_{50}$ of 12°. ITO destroys texture.
Honda *et al.* (Ref. 85)	Ti	CoCr (high pressure sputtering)	⋯	$\Delta\theta_{50}$ of 5° for thin recording layers.

work of Honda *et al.*, Ti underlayer was used. Although Honda *et al.* did not use any additional oxygen gas during the sputtering, they reported oxide based grain boundary.[85] In later works, Oikawa *et al.* have varied the thickness of Ru intermediate layer from 0–100 nm and have observed a reduction in the $\Delta\theta_{50}$, with the increase of Ru thickness.[128] The coercivity also increased from 500 to 2000 Oe, when Ru thickness was varied from 10 to 50 nm. Bertero *et al.* have used Ti(8 nm)/Ru(60 nm) as the intermediate layers and have obtained a $\Delta\theta_{50}$ value of 5.5°.[17] Inaba *et al.* have used Pt(10 nm)/Ru(10 nm) as the intermediate layers and have obtained a $\Delta\theta_{50}$ value of about 7°.[100] Keitoku *et al.* have used Ta/Ru intermediate layers and have obtained a $\Delta\theta_{50}$ value of about 9° for a Ru thickness of 10 nm. Shimatsu *et al.* have studied Pt, Pd, and Ru intermediate layers and have reported that the $\Delta\theta_{50}$ varied between 3° and 8° without specific details.[99,129] Park *et al.* have attempted to optimize the deposition pressure and temperature of Ru layer and have obtained a $\Delta\theta_{50}$ value of 4.5° at 30 nm of Ru.[130] They have also reported that a high temperature deposition of Ru led to Ru(100) peaks, which are not desirable for perpendicular recording application.

Choe *et al.* have studied Ta/Ru intermediate layers and have obtained a $\Delta\theta_{50}$ value of 3° for the Co layer.[14] They have also indicated that the SNR of the media depends strongly (at the rate of 0.6 dB per −1°) on the $\Delta\theta_{50}$. SNR depends on $\Delta\theta_{50}$ for at least two reasons: (i) If all the Co grains are oriented with the *c* axis perpendicular to the film plane, the component of M in the perpendicular direction will be higher, the signal will be larger, and the noise will be lower. (ii) If the easy axes of some small grains are not oriented in the perpendicular direction, their magnetization can be easily reversed because of demagnetizing fields and thermal effects. Such grains will be a source of noise. Therefore, it is clear that achieving a low value of $\Delta\theta_{50}$ is crucial for obtaining high performance from the recording media. However, it is also necessary to reduce the thickness of intermediate layer so as to increase the write field and to reduce the PW50 (pulse width at 50% of maximum height of isolated pulses). Calculations by Chang *et al.*, for example, indicate that lower head-to-keeper spacing will help to improve the writing and to reduce the PW50. In double-layered perpendicular recording media, the thickness of the intermediate layer will contribute to the head-to-keeper spacing. Therefore, it is necessary to reduce the intermediate layer thickness.[18] Litvinov *et al.* also have reported that the head-to-keeper spacing will decide the amount of write field available for the writing process.[27] In addition, it will also determine the width of the bits.

3. Morphology

Recently, intermediate layer has also been loaded with an additional role of producing the right morphology to control the segregation of grains in the recording layer. For example, in the study of and Park *et al.*,[130] Shi *et al.*,[131] and Mukai *et al.*,[132] it was noted that the deposition of Ru at higher pressures led to an increase in the value of $\Delta\theta_{50}$. On the other hand, sputtering Ru at higher pressures (Ru_2) leads to a segregated structure in both the Ru layer and in the recording layer and leads to an improved coercivity (and a lower noise). Nevertheless, the deposition of Ru at lower pressures (Ru_1) helps in achieving a narrow $\Delta\theta_{50}$. Therefore, in order to achieve both narrow $\Delta\theta_{50}$ and a high coercivity, dual Ru intermediate layers have been studied. Shi *et al.* have varied the thickness ratio of Ru_1 and Ru_2 layers and have reported that coercivity, nucleation field, and $\Delta\theta_{50}$ are optimum for intermediate values of thickness ratio than for pure Ru_1 or Ru_2 alone.[102] Mukai *et al.* have fixed the thickness of the Ru_2 layer to be about 3.7 nm and have increased the thickness of Ru_1 from 6 to 26 nm.[103] $\Delta\theta_{50}$ was found to decrease with the increase in thickness of Ru_1 layer, which was also accompanied by an increase of SNR. Shi *et al.* and Park *et al.* have also studied the effect of top Ru deposition pressure.[131,133] In the studies of both groups, improved grain isolation is observed for films which were made with higher pressure Ru on the top.

D. Recording layers

The material used for the recording layer of the perpendicular media has traditionally been a Co alloy. The CoCr alloy was the original media proposed by Iwasaki *et al.* in the late 1970s.[3] Since then, modifications of Co alloys such as CoCrPt, CoCrTa, CoCrNb, CoCrPtNb, and CoCrPtB were used as the recording layer material.[6,7,10,11,17,85,86,126] Even though the material and processes used in the perpendicular recording media were similar to that used in longitudinal recording media, the former could not exhibit competing performance until the end of the last century. The problems of the earlier generations of perpendicular media materials are described in the following subsection.

1. CoCr-alloy media

One of the major problems of CoCr-alloy media materials was that the nucleation field (field required to switch 5% of the magnetization) of the recording layer was seen in the first quadrant of the hysteresis loop.[134] This implies that at zero fields magnetization of several grains has already reversed. Such grains with reversed magnetization would exhibit a high dc noise. Figure 16 is an illustration to show the significance of nucleation field. The grains are magnetized into the plane of the paper with an applied field. When the field is removed, all the grains are expected to maintain the magnetization if they are thermally stable and their anisotropy energy is higher than that of the demagnetizing energy. However, if the anisotropy constant of the media is not high, some grains (smaller ones) would reverse, as in Fig. 16(a). However, if the anisotropy is high enough, all the grains would maintain their magnetization in the applied field direction, as in Fig. 16(b). This could be seen as hysteresis loops with nucleation fields in the first quadrant and second quadrant for media with low K_u and high K_u, respectively [Figs. 16(c) and 16(d)]. Therefore, media with high anisotropy are needed to obtain a negative nucleation field.

In the earlier days, it was difficult to obtain such media as Cr was used as an additive element to obtain the exchange decoupling. As a side effect, the presence of Cr led to media with lower anisotropy energy.[134] To overcome this problem,

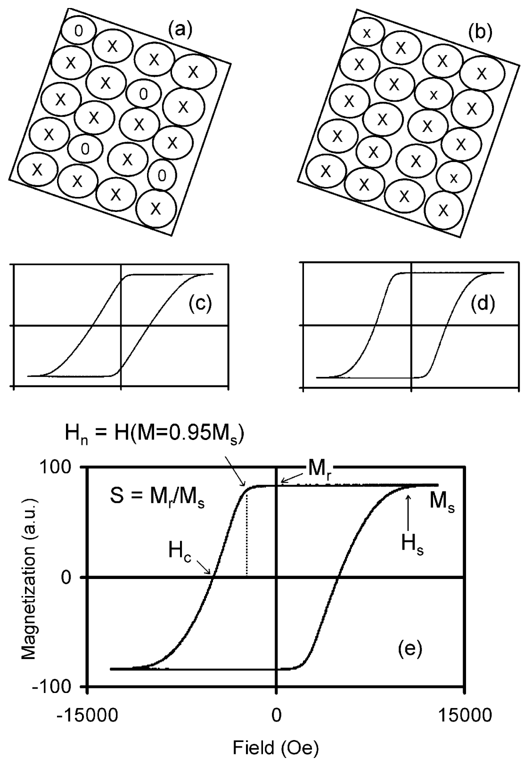

FIG. 16. (Top) Illustration of remanence magnetization state of grains of perpendicular media after it was saturated with a field into the plane. (a) Grains with a lower anisotropy constant show a reversal with remanent magnetization out of the plane showing instability. (b) Grains with a higher anisotropy constant show stable magnetization. (Middle) Illustration of hysteresis loops of the respective media that show (c) a positive H_n and (d) a negative H_n (bottom) hysteresis loop with relevant parameters.

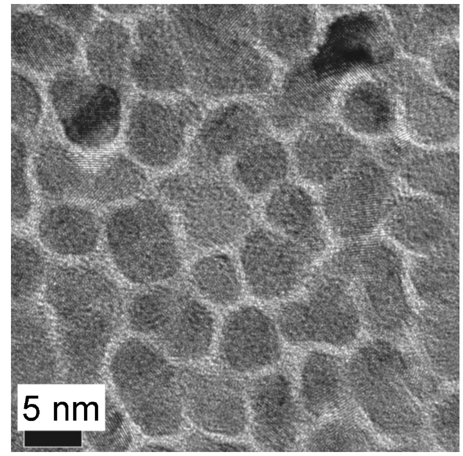

FIG. 17. TEM planar view of a typical CoCrPt:SiO_2 perpendicular recording medium.

Co/Pd multilayers were attempted as recording media.[94,135,136] Although Co/Pd multilayers could show unit squareness, they exhibited high transition noise. Novel concepts such as coupled granular continuous (CGC) media were proposed to draw the benefits of both granular and the continuous media.[9,137,138] In CGC media, the granular media is capped by a continuous media material such as Co/Pd multilayers. Because of such a capping layer, thermal stability of the grains in the granular layer increased. Lower noise and higher SNR could be obtained for optimum values of the continuous and granular layer thickness. CGC media are still considered as potential candidates for perpendicular recording, even with the introduction of CoCrPt-oxide recording media.

2. CoCrPt-oxide based media

Recently, oxide-based CoCrPt materials have received the attention of researchers. In these media, CoCrPt is sputtered together with an oxide such as Si-oxide or Cr-oxide. This oxide element can be present in the target or can be formed in the film during the reactive sputtering of target in an oxygen atmosphere.[17,99,100,117,129,139,140] As the oxide and Co do not mix well, Co alloy grain (dark regions in Fig. 17) is surrounded by an oxide based grain boundary (white regions in Fig. 17). In order to form this grain boundary (white regions in Fig. 17), the amount of Cr needed in the target material is not high. About 5–10 at. % of Cr is sufficient, as compared to 14–17 at. % of Cr needed in the CoCrPt media without oxides. Moreover, out of the 5–10 at. % of Cr available in the target, some of the Cr would oxidize and go to the grain boundary as well. As a result, the grain could have a low Cr in its core and a high anisotropy constant. Such grains would be thermally stable, and squareness close to one could be achieved. The oxide based grain boundary is also effective in reducing the grain size and in reducing the intergranular exchange interaction. Therefore, the noise can be reduced and sharper transitions are possible. Another advantage of oxide-based CoCrPt materials is that the manufacturing process will be more or less similar to that of longitudinal recording media. And, more importantly, small grain size, low noise, and good thermal stability could all be achieved with oxide-based media.

Although oxide-based Co alloys were investigated as early as 1994, only in the beginning of 2000 was serious attention paid to CoCrPt-oxide based media.[88,127] Oikawa *et al.* have studied CoCrPtO single-layered recording media and pointed out that the exchange coupling between the grains could be controlled by changing the oxygen content.[128] Hikosaka *et al.* have studied CoCrPtO media on FeAlSi soft magnetic underlayers.[114] Bertero *et al.* have compared the performance of CoCrPtB and CoCrPt-oxide perpendicular recording media.[17] Although they have obtained a larger SNR for CoCrPtB, they have pointed out that the CoCrPt-oxide media showed a larger squareness, higher coercivity, and lower number of stacking faults. Similar to Oikawa *et al.*, Bertero *et al.* also pointed out that the grain clustering in oxide based recording media is a problem. Oikawa *et al.* have studied CoCrPt with SiO_2 and pointed out that the addition of SiO_2 is very effective in isolating the grains. They reported grain sizes of about 7 nm with well-defined grain boundaries. They also pointed out that CoCrPt:SiO_2 media could show better recording performance than CoCrPtB perpendicular media. Since then, several research works have been published on oxide based CoCrPt recording media.

Zheng *et al.* have compared CoCrPtB and CoCrPt-oxide perpendicular recording media and have pointed out that the oxide based media can show better recording performance.[15]

TABLE III. Approximate requirements for high-density recording media and how they are related to the recording performance (in current products and for approximately 500 Gbits/in.^{2} areal density).

Parameter	Current products	500 Gbits/in.^{2}	Unit	Remarks
$M_r t$	0.7	0.7	memu/cm^3	Related to signal.
H_c	4000	6000	Oe	Related to storage, SNR, and T_{50}.
H_n	−2000	−3000	Oe	Related to thermal stability and erasure issues.
S	0.95–1	0.95–1	⋯	Related to dc noise.
S^*	0.5	0.5	⋯	Related to transition noise.
$\Delta\theta_{50}$	3.8	2–3	deg	Related to signal and noise.
Grain diameter D	7	5.7	nm	Related to SNR.
Grain size distribution	25%	15%	$\langle D\rangle/D$	Related to SNR and thermal stability.
H_k	12 000	19 000	Oe	Related to writability.

Choe *et al.* have studied the effect of slope dM/dH (at H_c) on the SNR, NLTS, and so on.[14] Media with smaller slopes were found to give rise to larger SNR than those with larger values of slope. A smaller slope indicates that the grains are exchange decoupled. Such decoupling will reduce the magnetic cluster size and, therefore, sharper transitions will be possible.

Typically, the grain size decreases with the addition of more oxygen or SiO_2. Zheng *et al.* have reported grains as small as 4 nm with 25% of oxygen.[35] Inaba *et al.* have reported grains with a mean diameter of 5.4 nm with 14% of SiO_2.[100] Although the addition of oxygen is expected to form the grain boundary, excessive content of oxygen would lead to grains that are superparamagnetic. Piramanayagam *et al.* have proposed stacked CoCrPt:SiO_2 layers to improve the SNR and maintain thermal stability.[141] In such structures, the bottom layers are deposited with more oxygen and would have a smaller grain size to obtain a high SNR. The top recording layers are deposited with less oxygen and would have a larger anisotropy constant and provide thermal stability. In a similar way, CoCrPt-oxide media with CoCrPtB layers have also been studied.[142] In such recording media schemes, the SNR peaks for optimal thickness ratio of CoCrPt-oxide and CoCrPtB layers. While the CoCrPt-oxide layer provides the optimal exchange decoupling and the grain size, CoCrPtB layer provides a larger negative nucleation field. The nucleation field, coercivity, and the slope of the hysteresis loops can be tailored by controlling the ratio of the thickness of the top and bottom layers. For these reasons, such stacked media provide improved overwrite and SNR without affecting the thermal stability. It is believed that such stacked media, where several layers complement each other in some form or the other, would be a common feature in all perpendicular recording media. Table III lists the macromagnetic properties expected from a typical recording medium candidate.

In order to improve the areal densities obtained by the existing candidates, it is also necessary to improve the thermal stability of the recording media. Shimatsu *et al.* have worked on media with a high K_{u2}.[99] The anisotropy energy of a Co grain with an uniaxial anisotropy is expressed as

$$E_a = K_{u0} + K_{u1}\sin^2\theta + K_{u2}\sin^4\theta. \tag{6}$$

In the above term, θ is the angle between the applied field and the anisotropy easy axis. K_{u1} and K_{u2} are the first and second order anisotropy constants. Usually, the K_{u2} term is neglected, as when K_{u2} is much smaller, the second term is negligible. On the other hand, if materials with high K_{u2} are discovered, it will help to improve the thermal stability. Since K_{u2} would help to improve the thermal stability without increasing the writing field, increasing K_{u2} of the recording media is an effective approach. Several underlayers such as Ru, Pd, and Pt have been deposited below the CoCrPt:SiO_2 recording layers to alter the K_{u2} term. It was observed that Pd is helpful to get a higher K_{u2}. Research efforts which will help to extend the life of CoCrPt-oxide based recording media by improving the thermal stability, writability, and SNR are described in Sec. V E.

E. Recent developments

The progress of the research work on CoCrPt-oxide based media will, as usual, be decided by SNR, thermal stability, and writability. From the media perspective, SNR improvement will be decided by the *c*-axis dispersion, grain size, and grain size distribution. Thermal stability is essentially decided by the materials used. Writability is determined by the media design, such as stacking of layers [e.g., exchange coupled composite (ECC) media] or through the design of thinner intermediate layers. This section captures some of the most recent developments.

1. Soft magnetic underlayers

In order to improve the writability and performance, several novel approaches have recently been introduced by Piramanayagam *et al.*[104,143] One approach involves replacing the amorphous SUL by a crystalline SUL. By using a suitable combination of seed layers, such as Ta/Ru, fcc-based soft underlayer such as FeCo could grow with a very good (111) texture. When the intermediate layer and the recording layer are grown on a fcc(111) template, epitaxial growth condition for hcp(002) is achieved (see Fig. 18). In such a design, the intermediate layer is needed only for exchange de-

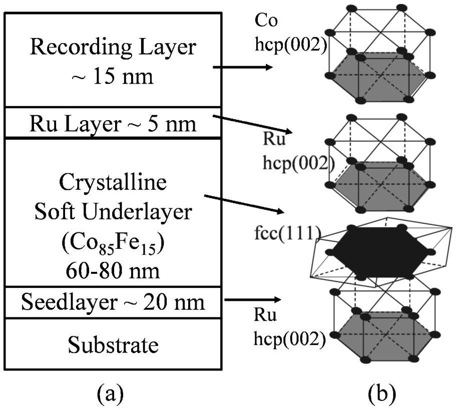

FIG. 18. Illustration of (a) media layer structure and (b) epitaxial growth of Ru and recording layer on crystalline FeCo SUL.

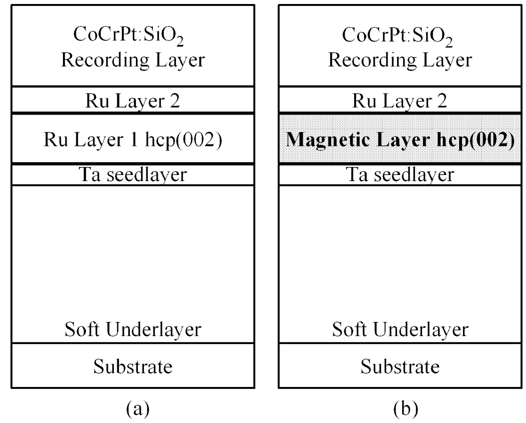

FIG. 19. Layer structure of media in (a) conventional perpendicular media with dual Ru layers and (b) advanced media with a magnetic intermediate layer.

coupling the soft underlayer and the recording layer and segregation of the grains. Therefore, the intermediate layer can be thinner than that needed with amorphous soft underlayers.

The media with crystalline soft underlayers also pose the challenges of higher roughness, larger noise, and larger grain size in the recording layer, which are yet to be resolved. On the other hand, roughness and noise are not issues in media with *a*-SUL. Therefore, an alternative approach that would make use of the best features of both amorphous and crystalline SUL could be an intermediate step toward high-density perpendicular recording. One such approach is a hybrid SUL, which is a stack of crystalline SUL on the amorphous SUL, proposed by Piramanayagam *et al.*[144] In the hybrid SUL, an amorphous layer at the bottom would provide a smooth surface and help to achieve low noise characteristics. The crystalline SUL, which is at the top, would contribute in the writing process as an SUL but would also provide a growth template for the layers above. With such a scheme, optimized values of roughness and *c*-axis orientation were obtained in media with hybrid SUL. Improvement in the writability was also observed. Such a hybrid SUL design also helps to replace a part of the expensive Ru layer in the intermediate layer.

2. Intermediate layers

As discussed before, reducing the thickness of the intermediate layers without increasing the $\Delta\theta_{50}$ of the recording layers is a challenging problem. It has been reported that reducing the thickness of intermediate layers increases the $\Delta\theta_{50}$. To overcome this problem, one possible approach is to search a suitable seed layer and intermediate layer combination, which could lead to lower $\Delta\theta_{50}$, for thin intermediate layers. In such an approach, Piramanayagam *et al.* have studied X/Pd/Ru intermediate layers and they have reported that the $\Delta\theta_{50}$ depends strongly on the material X.[107] Among several materials, the lowest $\Delta\theta_{50}$ has been achieved using a CrTi seed layer. Therefore, finding out a suitable combination of seed layer and intermediate layer is a possible way to reduce intermediate layer thickness. Finding out alternative materials for Ru may also be useful from the economic sense. The price of Ru has increased by three to four times in the last six months, and such a steep price increase is especially critical for the recording media industry, which sells the media at less than \$8 a disk.

Another novel approach involves a nonphysical way of reducing the intermediate layer thickness. In this approach, the nonmagnetic Ru_1 layer, which is needed for producing the hcp(00.2) texture, is replaced with a magnetic layer such as CoCr (Fig. 19). In this case, the magnetic material based intermediate layer would help to pass the flux from the head into the soft underlayer. In this case also, the ruthenium based intermediate layer is only needed for exchange decoupling and grain segregation. Media with magnetic intermediate layers showed recording performance comparable to that of media with conventional intermediate layers. The progress in this direction would depend on the search for suitable seed layers and magnetic intermediate layers with a high permeability which can provide a lower *c*-axis dispersion and the ways of controlling the noise arising from the introduction of magnetic layer.[106]

3. Recording layer

In order to continue the use of CoCrPt-oxide media, it will be necessary to identify suitable oxide materials as the recording layers or other methods that would form a narrow grain boundary but effectively decouple the grains. The new oxide materials should also help in achieving narrower grains and a narrower grain size distribution. The future media would also have a higher anisotropy constant to overcome the thermal instability issues by reducing the Cr content or by increasing the Pt content. Reducing the grain size and distribution of the existing CoCrPt-oxide media using other methods is also possible.

Recently, studies have been carried out along these lines to reduce the grain size and increase the thermal stability of the recording layer. Piramanayagam *et al.* have proposed an intermediate layer based approach to reduce the grain size of the recording layer.[145] In this approach, the intermediate layer Ru_2 is not pure Ru, but an alloy of RuCr. When a RuCr alloy is sputtered in the presence of reactive oxygen gas, Cr-based oxide would form the grain boundary (Fig. 20). By a suitable combination of pressure and Cr and oxygen com-

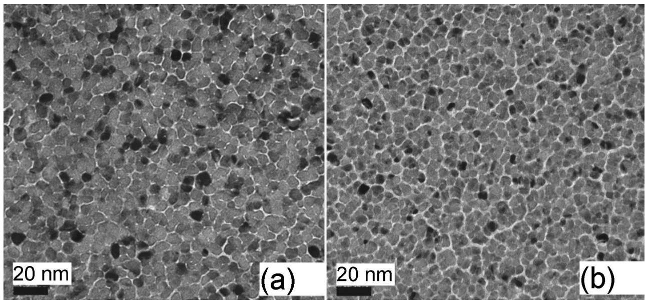

FIG. 20. TEM planar view of grains in (a) RuCr intermediate layer and (b) RuCr-oxide intermediate layer.

position, the grain size could be tailored. Piramanayagam *et al.* have reported a grain-to-grain distance of 6.4 nm based on this approach (Fig. 21).

In order to reduce the grain size of recording medium, Piramanayagam *et al.* have also proposed a synthetic nucleation layer (SN layer) approach.[144] In a polycrystalline thin film, such as a recording medium, the grain size is determined by the number of nucleation sites and the distribution is determined by the arrangement of the nucleation sites. When a recording medium is sputtered, the nucleation sites are randomly formed during the film deposition. Therefore, the grain size and the distribution cannot be controlled easily. However, if a dedicated nucleation layer (SN layer) can be formed, where the nucleation sites can be uniformly and densely distributed, the grain size and distribution can be controlled very easily. The SN layer can be found out using experimental methods or from film-growth simulations or both. The SN layer, inserted between the Ru1 and Ru2 layers [Fig. 19(a)], was found to help reduce the grain size of intermediate layer by about 1 nm. Grain sizes of about 5.8 nm (center-to-center separation) and much smaller grain diameters were obtained using this method. Grain size distribution was also reduced. Mukai *et al.* have also proposed a similar scheme to reduce the grain size, where they observed a grain size of 5.9 nm (grain diameter).[146] However, the nucleation layer was inserted below the Ru1 layer in the scheme of Mukai *et al.* Such methods have a potential to control and tailor the grain size in future perpendicular recording media.

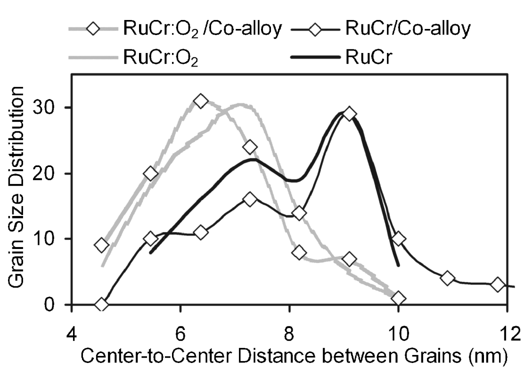

FIG. 21. Grain size distribution in CoCrPt:SiO_2 media deposited (a) RuCr intermediate layer and (b) RuCr-oxide intermediate layer.

VI. PERPENDICULAR RECORDING MEDIA FOR THE FUTURE

A. FePt media

As the areal density increases beyond 500 or 600 Gbits/in.^{2}, the recording media based on CoCrPt:SiO_2 could face a thermal instability problem. Therefore, alternative materials or methods of recording schemes are needed to move the magnetic recording industry forward.[147] One such material that has the potential to support high-density perpendicular recording is highly anisotropic FePt. Earlier studies on FePt films were focused on applications in magneto-optic recording.[148,149] However, recently, FePt films are considered for extremely high-density magnetic recording. Weller *et al.* have calculated that FePt could be thermally stable, even for grain sizes as small as 3 nm. If it is possible to make such small grains and if information could be well written on these materials, the areal density that can be achieved with FePt could easily surpass 1 Tbits/in.^{2}. With this idea in mind, several researchers have been working on FePt media.[150–157]

FePt thin film has a fcc phase when deposited at room temperature. This phase does not exhibit a high anisotropy. However, when annealed at temperatures as high as 600 °C, high anisotropic fct-FePt is formed. Such a high annealing temperature is not favorable for production. Therefore, Xu *et al.*[158] and several others have reported synthesizing FePt films with the L10 phase at low temperatures. The work of Xu *et al.* is based on the stress induced by the underlayer lattice to cause phase transformation at a low temperature. They have reported that at temperatures of 350 °C fct-FePt could be formed.[158]

Reducing the grain size of FePt is another challenge. Several methods such as doping FePt with Ag, Cu, or C, or laminating FePt with Ag, Cu, or C, or depositing underlayers and overlayers have been attempted by several researchers.[159] Shen *et al.* have achieved a grain size of 6.6 nm in FePt films deposited on RuAl underlayers.[160] Ko *et al.* have carried out detailed studies on FePt:C films. A grain size of about 4 nm has been obtained by 50% carbon doping. However, at this composition, the film showed the easy axis in-plane. Reducing the grain size to 4 nm with a low size distribution of 10% or below and controlling the intergranular interaction and perpendicular orientation are daunting tasks for the researchers to make FePt suitable for extremely high-density data storage.

B. Tilted recording media

Even if FePt media could be tailored to achieve the desired grain size, grain size distribution, exchange decoupling, and so on, writing information on FePt media would still be a challenge. Because of the high anisotropy constant, FePt media also have a high switching field. Therefore, when considering highly anisotropic materials for high-density recording, it is also essential to consider a way to write information on them. Gao and Bertram[161] have proposed a tilted recording scheme to write information on such media. If the anisotropy easy axis is tilted with respect to the applied field direction, then the effective writing field needed to switch the magnetization would be lower. Therefore, high anisotropy materials that cannot be used in the conventional perpendicular recording could be used in tilted recording. Although the simulation results are promising, there is not much experimental work on this type of media.[161,162]

C. Exchange-coupled composite media

As discussed earlier, writability will be a serious problem for media with high anisotropy. To overcome this problem, Victora and Shen proposed exchange-coupled composite media.[163] In this media, a soft magnetic grain and a hard magnetic grain are coupled to each other. When a reversal field is applied, the soft magnetic part will switch first, which will excite the reversal of the hard magnetic grain. With such a medium, the reversal field can be reduced. Wang *et al.* have carried out experimental work on such media with Co/Pd recording layer and FeSi soft layer.[164]

D. Percolated media

Another novel concept of media proposed to overcome the problem of thermal stability is percolated media.[165] In the conventional media, the grain size determines the bit boundaries. Therefore, the grain size needs to be reduced, which leads to thermal stability issues. On the other hand, if the reversal mechanism is based on pinning sites, the density of the pinning sites would determine the bit boundary. If the pinning sites have a high density, narrow transitions and high density could be achieved. Zhu and Tang have carried out simulation work, and Laughlin *et al.* have recently carried out experimental work on such recording media. They have proposed that CoPt sputtered together with SiO_2 could be potential candidates for percolated media. They have observed that when $CoPt-SiO_2$ is annealed at 600 °C, for about 1 min, oxide phase segregates and forms the pinning sites. They have reported that such oxide phase segregation could be one way to achieve pinning sites.[166]

In addition to the several methods described above, the research community is also considering other technologies, such as heat-assisted magnetic recording,[167,168] discrete-track recording,[169] and patterned media recording.[170–173] While these advanced methods would also make use of perpendicular recording, significant changes in the media fabrication or head fabrication or both are expected. A delay in the introduction of any of these exotic technologies is preferred, as the hard disk drive and media industry has just recently made significant investments to move to perpendicular recording. It is hoped that the existing technology can be exploited to the extreme that these new methods need not be used in the hard disk drives at least for the next five years.

VII. SUMMARY

In this paper, the latest developments on perpendicular recording media have been reviewed in a systematic way.

- In the state-of-the-art perpendicular recording media, soft magnetic underlayers with antiparallel coupling are being used to minimize the spike noise. Radial anisotropy, induced by a magnetic field during the deposition/post deposition annealing helps to reduce dc noise.
- Ru alloys with Ta or other seed layers are used as intermediate layers. Oxide based CoCrPt alloys are used as the recording layer.
- A grain size of about 6.4 nm has been achieved in $CoCrPt:SiO_2$ media with RuCr:oxide intermediate layers.
- FePt films are being considered for future perpendicular recording media.
- Several novel concepts, such as tilted perpendicular recording, exchange-coupled composite media, and percolated media, have been proposed by different researchers to extend the perpendicular magnetic recording to higher densities.

[1] S. Iwasaki and K. Takemura, IEEE Trans. Magn. **11**, 1173 (1975).
[2] S. Iwasaki and Y. Nakamura, IEEE Trans. Magn. **14**, 436 (1978).
[3] S. Iwasaki, Y. Nakamura, and K. Ouchi, IEEE Trans. Magn. **15**, 1456 (1979).
[4] M. Futamoto, Y. Honda, H. Kashiwase, and K. Yoshida, IEEE Trans. Magn. **21**, 1426 (1985).
[5] Y. Hirayama, M. Futamoto, K. Ito, Y. Honda, and Y. Maruyama, IEEE Trans. Magn. **33**, 996 (1997).
[6] Y. Hirayama, M. Futamoto, K. Kimoto, and K. Usami, IEEE Trans. Magn. **32**, 3807 (1996).
[7] Y. Hirayama, Y. Honda, T. Takeuchi, and M. Futamoto, IEEE Trans. Magn. **35**, 2766 (1999).
[8] Y. Honda, A. Kikukawa, Y. Hirayama, and M. Futamoto, IEEE Trans. Magn. **36**, 2399 (2000).
[9] H. Muraoka, Y. Sonobe, K. Miura, A. M. Goodman, and Y. Nakamura, IEEE Trans. Magn. **38**, 1632 (2002).
[10] H. Uwazumi, T. Shimatsu, Y. Sakai, A. Otsuki, I. Watanabe, H. Muraoka, and Y. Nakamura, IEEE Trans. Magn. **37**, 1595 (2001).
[11] J. Ariake, N. Honda, K. Ouchi, and S. Iwasaki, IEEE Trans. Magn. **36**, 2411 (2000).
[12] J. Ariake, N. Honda, K. Ouchi, and S. Iwasaki, IEEE Trans. Magn. **36**, 2399 (2000).
[13] B. R. Acharya, J. N. Zhou, M. Zheng, G. Choe, E. N. Abarra, and K. E. Johnson, IEEE Trans. Magn. **40**, 2383 (2004).
[14] G. Choe, M. Zheng, E. N. Abarra, B. G. Demczyk, J. N. Zhou, B. R. Acharya, and K. E. Johnson, J. Magn. Magn. Mater. **287**, 159 (2004).
[15] M. Zheng, G. Choe, A. Chekanov, B. G. Demczyk, B. R. Acharya, and K. E. Johnson, IEEE Trans. Magn. **39**, 1919 (2003).
[16] H. S. Jung and W. D. Doyle, IEEE Trans. Magn. **39**, 679 (2003).
[17] G. A. Bertero *et al.*, IEEE Trans. Magn. **38**, 1627 (2002).
[18] C. Chang *et al.*, IEEE Trans. Magn. **38**, 1637 (2002).
[19] M. Xiao, B. Wilson, K. Takano, H. Do, Y. Ikeda, and H. Rosen, IEEE Trans. Magn. **41**, 3154 (2005).
[20] K. W. Wierman, T. J. Klemmer, B. Lu, G. Ju, and K. J. Howard, J. Appl. Phys. **91**, 8031 (2002).
[21] T. Oikawa, M. Nakamura, H. Uwazumi, T. Shimatsu, H. Muraoka, and Y. Nakamura, IEEE Trans. Magn. **38**, 1976 (2002).
[22] M. Mallary, A. Torabi, and M. Benakli, IEEE Trans. Magn. **38**, 1719 (2002).
[23] K. Ise, K. Yamakawa, N. Honda, K. Ouchi, H. Muraoka, and Y. Nakamura, IEEE Trans. Magn. **39**, 2374 (2003).
[24] S. Iwasaki, IEEE Trans. Magn. **20**, 657 (1984).
[25] K. Ouchi and N. Honda, IEEE Trans. Magn. **36**, 16 (2000).
[26] J. H. Judy, J. Magn. Magn. Mater. **287**, 16 (2004).
[27] D. Litvinov, M. H. Kryder, and S. Khizroev, J. Magn. Magn. Mater. **241**, 453 (2002).
[28] D. Litvinov, M. H. Kryder, and S. Khizroev, J. Magn. Magn. Mater. **232**, 84 (2001).
[29] D. Litvinov and S. Khizroev, J. Appl. Phys. **97**, 071101 (2005).
[30] S. Khizroev and D. Litvinov, J. Appl. Phys. **95**, 4521 (2004).
[31] D. E. Laughlin, Y. C. Feng, D. N. Lambeth, L. L. Lee, and L. Tang, J. Magn. Magn. Mater. **155**, 146 (1996).

[32]L. L. Lee, D. E. Laughlin, L. Fang, and D. N. Lambeth, IEEE Trans. Magn. **31**, 2728 (1995).
[33]B. R. Acharya, A. Inomata, E. N. Abarra, A. Ajan, D. Hasegawa, and I. Okamoto, J. Magn. Magn. Mater. **260**, 261 (2003).
[34]B. R. Acharya, E. N. Abarra, and I. Okamoto, IEEE Trans. Magn. **37**, 1475 (2001).
[35]M. Zheng, B. R. Acharya, G. Choe, J. N. Zhou, Z. D. Yang, E. N. Abarra, and K. E. Johnson, IEEE Trans. Magn. **40**, 2498 (2004).
[36]G. Choe, IEEE Trans. Magn. **31**, 2809 (1995).
[37]B. B. Lal, M. Tobise, and T. Shinohara, IEEE Trans. Magn. **30**, 3954 (1994).
[38]T. Kanbe, Y. Takahashi, K. Tanahashi, A. Ishikawa, and Y. Hosoe, IEEE Trans. Magn. **35**, 2667 (1999).
[39]T. Kanbe, Y. Yahisa, H. Suzuki, H. Kataoka, Y. Takahashi, and Y. Hirayama, J. Appl. Phys. **91**, 8611 (2002).
[40]S. N. Piramanayagam, Y. F. Xu, D. Y. Dai, L. Huan, S. I. Pang, and J. P. Wang, J. Appl. Phys. **91**, 7685 (2002).
[41]D. Djayaprawira, M. Mikami, S. Yoshimura, and M. Takahashi, IEEE Trans. Magn. **39**, 2258 (2003).
[42]L. L. Lee, D. E. Laughlin, and D. N. Lambeth, IEEE Trans. Magn. **34**, 1561 (1998).
[43]Y. F. Xu, J. P. Wang, C. K. Pock, X. Cheng, Z. S. Shan, and T. C. Chong, IEEE Trans. Magn. **37**, 1491 (2001).
[44]D. Weller and M. F. Doerner, Annu. Rev. Mater. Sci. **30**, 611 (2000).
[45]T. Kanbe, I. Tamai, Y. Takahashi, K. Tanahashi, and Y. Hosoe, IEEE Trans. Magn. **33**, 2980 (1997).
[46]E. W. Singleton, P. B. Narayan, W. Xiong, R. Raman, and H.-L. Hoo, J. Appl. Phys. **85**, 5840 (1999).
[47]S. Ohkijima, M. Oka, and H. Murayama, IEEE Trans. Magn. **33**, 2944 (1997).
[48]K. Tanahashi, I. Tamai, Y. Takahashi, T. Kanbe, and Y. Hosoe, J. Magn. Magn. Mater. **193**, 232 (1999).
[49]K. E. Johnson, M. Mirzamaani, and M. F. Doerner, IEEE Trans. Magn. **31**, 2721 (1995).
[50]D. N. Lambeth, E. M. T. Velu, G. Bellesis, L. L. Lee, and D. E. Laughlin, J. Appl. Phys. **79**, 4496 (1996).
[51]H. Takano, T. T. Lam, J. G. Zhu, and J. H. Judy, IEEE Trans. Magn. **29**, 3709 (1993).
[52]C. H. Hee and J. P. Wang, Appl. Phys. Lett. **81**, 3038 (2002).
[53]G. Choe *et al.*, IEEE Trans. Magn. **39**, 633 (2003).
[54]A. Ajan and I. Okamoto, Appl. Phys. Lett. **81**, 1465 (2002).
[55]T. Yogi and T. A. Nguyen, IEEE Trans. Magn. **29**, 307 (1993).
[56]N. Inaba and M. Futamoto, J. Appl. Phys. **87**, 6863 (2000).
[57]C. R. Paik, I. Suzuki, N. Tani, M. Ishikawa, Y. Ota, and K. Nakamura, IEEE Trans. Magn. **28**, 3084 (1992).
[58]M. P. Sharrock, J. Appl. Phys. **76**, 6413 (1994).
[59]G. Bayreuther, P. Bruno, G. Lugert, D. Renard, and C. Turtur, Thin Solid Films **175**, 341 (1989).
[60]H. J. Richter, S. Z. Wu, and R. Malmhall, IEEE Trans. Magn. **34**, 1540 (1998).
[61]M. Alex and D. Wachenschwanz, IEEE Trans. Magn. **35**, 2796 (1999).
[62]A. Moser and D. Weller, IEEE Trans. Magn. **35**, 2808 (1999).
[63]A. Moser, D. Weller, M. E. Best, and M. F. Doerner, J. Appl. Phys. **85**, 5018 (1999).
[64]T. Pan and G. W. D. Spratt, IEEE Trans. Magn. **32**, 3623 (1996).
[65]L. S. Prichard and K. O'Grady, J. Magn. Magn. Mater. **193**, 220 (1999).
[66]S. M. Stinnett, W. D. Doyle, P. J. Flanders, and C. Dawson, IEEE Trans. Magn. **34**, 1828 (1998).
[67]S. M. Stinnett, J. W. Harrell, A. F. Khapikov, and W. D. Doyle, IEEE Trans. Magn. **36**, 148 (2000).
[68]S. H. Charap, P. L. Lu, and Y. J. He, IEEE Trans. Magn. **33**, 978 (1997).
[69]E. N. Abarra, B. R. Acharya, A. Inomata and I. Okamoto, IEEE Trans. Magn. **37**, 1426 (2001).
[70]E. E. Fullerton, D. T. Margulies, A. Moser, and K. Takano, Solid State Technol. **44**, 87 (2002).
[71]J. Lohau, A. Moser, D. T. Margulies, E. E. Fullerton, and M. E. Schabes, Appl. Phys. Lett. **78**, 2748 (2002).
[72]D. T. Margulies, M. E. Schabes, W. McChesney, and E. E. Fullerton, Appl. Phys. Lett. **80**, 91 (2002).
[73]M. E. Schabes, E. E. Fullerton, and D. T. Margulies, IEEE Trans. Magn. **37**, 1432 (2001).
[74]J. P. Wang, Z. S. Shan, S. N. Piramanayagam, and T. C. Chong, IEEE Trans. Magn. **37**, 1445 (2001).
[75]C. H. Hee, J. P. Wang, S. N. Piramanayagam, and T. C. Chong, Appl. Phys. Lett. **79**, 1646 (2002).
[76]S. I. Pang, S. N. Piramanayagam, and J. P. Wang, Appl. Phys. Lett. **80**, 616 (2002).
[77]S. N. Piramanayagam, C. H. Hee, and J. P. Wang, J. Appl. Phys. **90**, 3442 (2001).
[78]S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).
[79]S. N. Piramanayagam, J. P. Wang, Z. S. Shan, S. I. Pang, X. Shi, C. K. Pock, and T. C. Chong, IEEE Trans. Magn. **37**, 1438 (2001).
[80]S. N. Piramanayagam, J. P. Wang, C. H. Hee, S. I. Pang, T. C. Chong, Z. S. Shan, and L. Huang, Appl. Phys. Lett. **79**, 2423 (2001).
[81]S. N. Piramanayagam, J. P. Wang, and S. I. Pang, IEEE Trans. Magn. **39**, 657 (2003).
[82]D. Litvinov and S. Khizroev, *Perpendicular Magnetic Recording* (Kluwer Academic, Dordrecht, 2005).
[83]N. Watanabe, Y. Ishizaka, K. Kimura, and E. Imaoka, IEEE Trans. Magn. **21**, 1368 (1985).
[84]S. Iwasaki, K. Ouchi, K. Saik, and M. Kimura, IEEE Trans. Magn. **22**, 1158 (1986).
[85]N. Honda, J. Ariake, K. Ouchi, and S. Iwasaki, IEEE Trans. Magn. **30**, 4023 (1994).
[86]N. Honda, J. Ariake, and K. Ouchi, IEEE Trans. Magn. **34**, 1651 (1998).
[87]T. Fujiwara, IEEE Trans. Magn. **21**, 1480 (1985).
[88]A. Morisako, M. Matsumoto, and M. Naoe, J. Appl. Phys. **79**, 4881 (1996).
[89]B. R. Acharya, S. Prasad, N. Venkataramani, S. N. Shringi, and R. Krishnan, J. Appl. Phys. **79**, 478 (1996).
[90]W. W. Jiang, J. P. Wang, and T. C. Chong, J. Appl. Phys. **91**, 8067 (2002).
[91]A. G. Roy, D. E. Laughlin, T. J. Klemmer, K. Howard, S. Khizroev, and D. Litvinov, J. Appl. Phys. **89**, 7531 (2001).
[92]L. Wu, T. Kita, N. Honda, and K. Ouchi, J. Magn. Magn. Mater. **193**, 89 (1999).
[93]S. N. Piramanayagam, M. Matsumoto, A. Morisako, and D. Kadowaki, IEEE Trans. Magn. **33**, 3247 (1997).
[94]Y. Uesaka, M. Koizumi, N. Tsumita, O. Kitakami, and H. Fujiwara, J. Appl. Phys. **57**, 3925 (1985).
[95]W. Cain, A. Payne, M. Baldwinson, and R. Hempstead, J. Appl. Phys. **32**, 97 (1996).
[96]D. Thomson, J. Magn. Soc. Jpn. **21**, 9 (1997).
[97]A. Inomata, E. N. Abarra, A. Ajan, M. Shinohara, and Y. Miura, IEEE Trans. Magn. **39**, 2276 (2003).
[98]H. Yamane, S. Watanabe, J. Ariake, N. Honda, K. Ouchi, and S. Iwasaki, J. Magn. Magn. Mater. **287**, 153 (2004).
[99]T. Shimatsu *et al.*, IEEE Trans. Magn. **41**, 3175 (2005).
[100]Y. Inaba, T. Shimatsu, T. Oikawa, H. Sato, H. Aoi, H. Muraoka, and Y. Nakamura, IEEE Trans. Magn. **40**, 2486 (2004).
[101]Y. Hsu *et al.*, IEEE Trans. Magn. **43**, 605 (2007).
[102]J. Z. Shi, S. N. Piramanayagam, C. S. Mah, H. B. Zhao, J. M. Zhao, and Y. S. Kay, Appl. Phys. Lett. **87**, 222503 (2005).
[103]R. Mukai, T. Uzumaki, and A. Tanaka, IEEE Trans. Magn. **41**, 3169 (2005).
[104]S. N. Piramanayagam, H. B. Zhao, J. Z. Shi, and C. S. Mah, Appl. Phys. Lett. **88**, 092501 (2006).
[105]S. N. Piramanayagam, J. Z. Shi, H. B. Zhao, C. S. Mah, and J. Zhang, IEEE Trans. Magn. **41**, 3190 (2005).
[106]Y. Honda, K. Tanahashi, Y. Hirayama, A. Kikukawa, and M. Futamoto, IEEE Trans. Magn. **37**, 1315 (2001).
[107]S. N. Piramanayagam, H. B. Zhao, J. Z. Shi, and C. S. Mah, Appl. Phys. Lett. **88**, 092506 (2006).
[108]J. R. Desserre, IEEE Trans. Magn. **20**, 663 (1984).
[109]A. Kikukawa, K. Tanahashi, Y. Honda, Y. Hiroyama, and M. Futamoto, J. Magn. Magn. Mater. **235**, 68 (2001).
[110]C.-H. Lai and R.-F. Jiang, J. Appl. Phys. **93**, 8155 (2003).
[111]M. Miura, H. Katahashi, K. Muramori, and M. Kajiyama, IEEE Trans. Magn. **24**, 2215 (1988).
[112]K. Sato, H. Wakamatsu, and M. Shinohara, IEEE Trans. Magn. **29**, 3730 (1993).
[113]S. Otomo, J. Jpn. Inst. Met. **60**, 529 (1996).
[114]T. Hikosaka, F. Nakamura, S. Oikawa, A. Takeo, and Y. Tanaka, IEEE Trans. Magn. **37**, 1586 (2001).
[115]E. W. Soo, T. J. Zhou, and J. P. Wang, J. Appl. Phys. **91**, 8019 (2002).
[116]K. Tanahashi, A. Kikukawa, Y. Takahashi, and Y. Hosoe, J. Appl. Phys. **93**, 6766 (2003).
[117]H. Uwazumi, N. Nakajima, M. Masuda, T. Kawata, S. Takenoiri, S. Wa-

tanabe, Y. Sakai, and K. Enomoto, IEEE Trans. Magn. **40**, 2392 (2004).
[118]T. Asahi, T. Yokoshima, J. Kawaji, T. Osaka, H. Ohta, M. Ohmori, and H. Sakai, IEEE Trans. Magn. **49**, 2356 (2004).
[119]T. Ando and T. Nishihara, IEEE Trans. Magn. **37**, 1228 (2001).
[120]T. Ando and T. Nishihara, IEEE Trans. Magn. **33**, 2983 (1997).
[121]K. Tanahashi, R. Arai, and Y. Hosoe, IEEE Trans. Magn. **41**, 577 (2005).
[122]J. N. Zhou, B. R. Acharya, P. Gill, E. N. Abarra, M. Zheng, and G. Choe, IEEE Trans. Magn. **41**, 3160 (2005).
[123]S. Das, S.-H. Kong, and S. Nakagawa, IEEE Trans. Magn. **40**, 2464 (2004).
[124]Y. Hirayama, A. Kikukawa, Y. Honda, N. Shimizu, and M. Futamoto, IEEE Trans. Magn. **36**, 2396 (2000).
[125]Y. Hirayama, I. Tamai, I. Takekuma, and Y. Hosoe, IEEE Trans. Magn. **32**, 2282 (2003).
[126]Y. Hirayama, M. Futamoto, K. Ito, Y. Honda, and Y. Maruyama, IEEE Trans. Magn. **33**, 996 (1997).
[127]T. Hikosaka, T. Komai, and Y. Tanaka, IEEE Trans. Magn. **30**, 4026 (1994).
[128]S. Oikawa, A. Takeo, T. Hikosaka, and Y. Tanaka, IEEE Trans. Magn. **36**, 2393 (2000).
[129]T. Shimatsu *et al.*, IEEE Trans. Magn. **41**, 566 (2005).
[130]J. W. Park, Y. K. Kim, T. H. Lee, H.-S. Oh, and B.-K. Lee, Phys. Status Solidi A **201**, 1763 (2004).
[131]J. Z. Shi, S. N. Piramanayagam, C. S. Mah, and J. M. Zhao, J. Magn. Magn. Mater. **303**, e145 (2006).
[132]R. Mukai, T. Uzumaki, and A. Tanaka, J. Appl. Phys. **97**, 10N119 (2005).
[133]S. H. Park, S. O. Kim, T. D. Lee, H. S. Oh, Y. S. Kim, N. Y. Par, and D. H. Hong, J. Appl. Phys. **99**, 08E701 (2006).
[134]T. Shimatsu, H. Uwazumi, Y. Sakai, A. Otsuki, I. Watanabe, H. Muraoka, and Y. Nakamura, IEEE Trans. Magn. **37**, 1567 (2001).
[135]L. Wu, T. Kita, N. Honda, and K. Ouchi, J. Magn. Magn. Mater. **193**, 89 (1999).
[136]S. N. Piramanayagam, M. Matsumoto, A. Morisako, and D. Kadowaki, IEEE Trans. Magn. **33**, 3247 (1997).
[137]Y. Sonobe *et al.*, IEEE Trans. Magn. **37**, 1667 (2001).
[138]Y. Sonobe *et al.*, IEEE Trans. Magn. **38**, 2006 (2002).
[139]T. Shimatsu, T. Oikawa, Y. Inaba, H. Sato, I. Watanabe, H. Aoi, H. Muraoka, and Y. Nakamura, IEEE Trans. Magn. **40**, 2461 (2004).
[140]Y. Inaba, T. Shimatsu, H. Muraoka, J. D. Dutson, and K. O'Grady, IEEE Trans. Magn. **41**, 3130 (2005).
[141]S. N. Piramanayagam, J. Z. Shi, H. B. Zhao, C. S. Mah, and J. Zhang, IEEE Trans. Magn. **41**, 3190 (2005).
[142]B. R. Acharya, M. Zheng, G. Choe, M. Yu, P. Gill, and E. N. Abarra, IEEE Trans. Magn. **41**, 3145 (2005).
[143]S. N. Piramanayagam, J. Z. Shi, H. B. Zhao, C. S. Mah, J. R. Shi, J. M. Zhao, J. Zhang, and Y. S. Kay, J. Magn. Magn. Mater. **303**, 287 (2006).
[144]S. N. Piramanayagam, C. K. Pock, L. Li, C. Y. Ong, C. S. Mah, and J. Z. Sh, Appl. Phys. Lett. **89**, 162504 (2006).
[145]S. N. Piramanayagam *et al.*, Joint MMM/Intermag Conference, Baltimore, 2007 (unpublished), Paper No. AB-01.
[146]R. Mukai and T. Uzumaki, Joint MMM/Intermag Conference, Baltimore, 2007 (unpublished), Paper No. EB-05.
[147]D. Weller and A. Moser, IEEE Trans. Magn. **35**, 4423 (1999).
[148]D. Weller, H. Brandle, G. Gorman, C.-J. Lin, and H. Notrays, Appl. Phys. Lett. **61**, 2726 (1992).
[149]M. Watanabe and M. Homma, Jpn. J. Appl. Phys., Part 2 **35**, L1264 (1996).
[150]G. Sáfrán, T. Suzuki, K. Ouchi, P. B. Barna, and G. Radnóczi, Thin Solid Films **496**, 580 (2005).
[151]A. K. Singh, J. Yin, and T. Suzuki, IEEE Trans. Magn. **41**, 3205 (2005).
[152]B. Bian, D. E. Laughlin, K. Sato, and Y. Hirotsu, IEEE Trans. Magn. **36**, 3021 (2000).
[153]C. Y. Tan, Y. Z. Zhou, J. S. Chen, S. Y. Chow, and G. M. Chow, J. Magn. Magn. Mater. **287**, 172 (2004).
[154]Y.-C. Wu, C.-H. Lai, C.-C. Chiang, and R. T. Huang, IEEE Trans. Magn. **41**, 3199 (2005).
[155]T. Suzuki, Z. Zhang, A. K. Singh, J. Yin, A. Perumal, and H. Osawa, IEEE Trans. Magn. **41**, 555 (2005).
[156]H. Ito, T. Shima, K. Takanashi, Y. K. Takahashi, and K. Hono, IEEE Trans. Magn. **41**, 3373 (2005).
[157]F. T. Yuan, S. K. Chen, L. Horng, and J. L. Tsai, IEEE Trans. Magn. **41**, 3346 (2005).
[158]Y. F. Xu, J. S. Chen, and J. P. Wang, Appl. Phys. Lett. **80**, 3325 (2002).
[159]T. Shima, T. Moriguchi, S. Mitani, and K. Takanashi, Appl. Phys. Lett. **80**, 288 (2002).
[160]W. K. Shen, J. H. Judy, and J. P. Wang, J. Appl. Phys. **97**, 10H301 (2005).
[161]K. Gao and H. N. Bertram, IEEE Trans. Magn. **38**, 3675 (2002).
[162]C. H. Hee, Y. Y. Zou, and J. P. Wang, J. Appl. Phys. **91**, 8004 (2002).
[163]R. H. Victora and X. Shen, IEEE Trans. Magn. **41**, 537 (2005).
[164]J. P. Wang, W. K. Shen, and J. Bai, IEEE Trans. Magn. **41**, 3181 (2006).
[165]J. G. Zhu and Y. H. Tang, J. Appl. Phys. **99**, 08Q903 (2006).
[166]D. E. Laughlin, Y. Peng, Y. Qin, M. Lin, and J. G. Zhu, IEEE Trans. Magn. **43**, 693 (2007).
[167]R. E. Rottmayer *et al.*, IEEE Trans. Magn. **42**, 2417 (2006).
[168]J.-U. Thiele, S. Maat, and E. E. Fullerton, Appl. Phys. Lett. **82**, 2859 (2003).
[169]D. Wachenschwanz, W. Jiang, E. Roddick, A. Homola, P. Dorsey, B. Harper, D. Treves, and C. Bajorek, IEEE Trans. Magn. **41**, 670 (2005).
[170]B. D. Terris and T. Thomson, J. Phys. D **38**, R199 (2005).
[171]C. A. Ross, Annu. Rev. Mater. Res. **31**, 203 (2001).
[172]H. Richter *et al.*, Appl. Phys. Lett. **88**, 222512 (2006).
[173]R. Sbiaa and S. N. Piramanayagam, Recent Patents on Nanotechnology **1**, 29 (2007).