# Perpendicular Recording: A Future Technology or a Temporary Solution

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**Abstract**

During the vitally critical times to the future advances in data storage technologies, perpendicular magnetic recording [1,2,3] has attracted a substantial amount of attention as a prime alternative to the technologies in place today [4,5]. As envisioned by the industry and academia leaders, perpendicular recording is the most likely candidate for the technology implemented in the next generations of hard drives. The most competitive virtue of this technology is the fact that while being technically the closest alternative to conventional longitudinal recording, it is capable of extending the (superparamagnetic) density limit [6] beyond what is achievable with longitudinal recording. It is widely believed that perpendicular magnetic recording paradigm will enable to sustain the current great strides in technological advances for the next several generations of magnetic storage solutions.

This paper will cover the basic principles underlying perpendicular recording as well as the challenges associated with implementing the technology [7,8,9,10].

## 1 Superparamagnetic limit and the need for a new technology

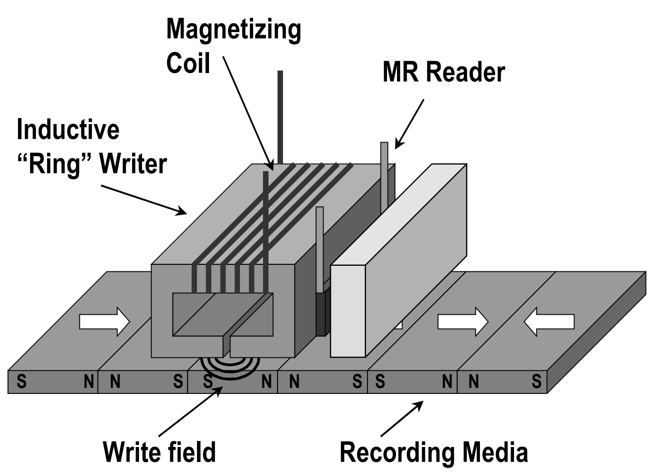
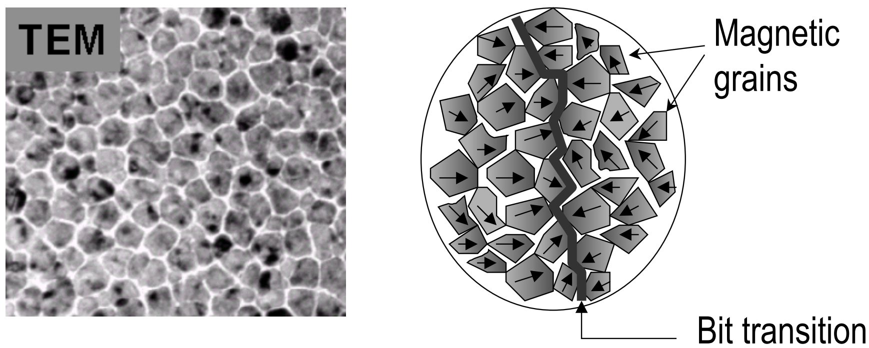



Figure 1. A schematic of a conventional longitudinal recording scheme employed in today's hard drives.

The data on a magnetic recording medium is stored by means of recording a certain spatial variations of the magnetization, where the magnetization variations represent the data. The relation between the data and the magnetization pattern is defined by the encoding scheme used. Figure 1 shows a simplified schematic of a conventional longitudinal recording system. The recording media are engineered such that the preferred direction of the magnetization, a so-called easy axis, lies in the plane of the recording layer. Using an inductive “ring”-type writer, the magnetization of the grains is aligned along the track in either positive or negative direction. The data is read back using a magnetoresistive element. A change or no change in the magnetization direction at the bit transitions corresponds to a 1 or to a 0, respectively. The lateral dimensions of a bit, i.e. the smallest feature realized in a particular drive design, defines the areal bit density that such a drive supports.

A conventional magnetic medium has granular structure such that each bit consists of several magnetic grains or magnetic clusters. The magnetic clusters/grains are usually shaped irregularly and are randomly packed, as shown in Figure 2a.  Consequently, the recording bits and bit transitions are usually not perfect, which is illustrated in Figure 2b. These imperfections lead to noise in the playback signal. The noise is kept below a certain acceptable level by means of including a sufficiently large number of magnetic grains into each bit. The resulting averaging reduces the level of noise. As the areal density increases, the bit size and the size of the grains that constitute the bit, decreases. Typical grains in today’s media range from 5 to 15nm.




(a) (b)

Figure 2. (a) A transmission electron micrograph of a typical granular medium; (b) a schematic of a single bit transition in a granular medium.

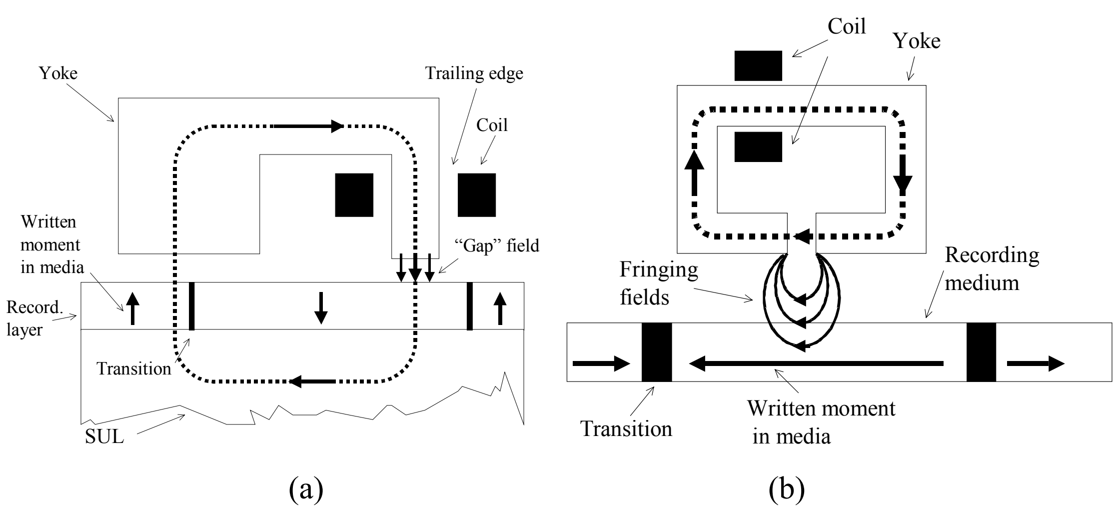
One of the critical factors characterizing the reliability of a data storage device is data stability. Various parameters control the stability of the data against the external factors. With respect to the external temperature, which is manifested by thermal fluctuations in the recording media, the magnetic anisotropy energy stored in each magnetic grain is one of the major determinants (assuming that the grains are magnetically independent). The magnetic anisotropy energy approximately defines the amount of energy necessary to reverse the direction of the magnetization of a grain. For a single grain, it is equal to $K_UV$, where $K_U$ is the magnetic anisotropy energy per unit volume and V is the volume of the grain. For a medium to be thermally stable, the above quantity $K_UV$ should be substantially greater (30-40 times) than the energy of a single quantum of thermal fluctuation, $k_BT$, where $k_B$ is Boltzman’s constant and T is the temperature [6]. As mentioned above, the higher areal densities require smaller grain sizes. It follows that to sustain thermal stability, $K_U$ of a magnetic medium material should increase with the grain size decreases. Unfortunately, as $K_U$ increases, so does the write field necessary to efficiently write onto the medium. In conventional longitudinal recording, the upper limit of the write field that a recording head can generate is equal to $2\pi M_S$ where $M_S$ is the saturation magnetization moment of the head material. The highest value of $4\pi M_S$ of the materials available today is rapidly approaching what is believed to be a fundamental limit of ~25kGauss. This defines the upper limit of the $K_U$ values that can be employed in a longitudinal medium and, consequently, the maximum areal density achievable with conventional longitudinal recording. It has been predicted that with the materials available today, the highest areal density achievable with conventional longitudinal recording is ~100Gbit/in$^2$ [5,6].

## 2 Dodging the superparamagnetic limit … The advantages of perpendicular recording?

Several aspects native to perpendicular recording make it superior to longitudinal recording with respect to the superparamagnetic limit. Among the advantages are higher write-field amplitude and sharper write-field gradients, thicker recording layers, absence of demagnetizing field at bit transitions, higher playback amplitude, etc. The specific nature of these advantages is discussed in detail below.

### 2.1 Higher write field with sharper side and trailing gradients

Figure 3 shows a comparative schematic of conventional longitudinal and perpendicular recording schemes. While in longitudinal recording, the natural direction of the magnetization, the easy axis, lies in the plane of a recording medium, in perpendicular recording, the easy axis is perpendicular to the plane of a medium. In longitudinal recording, the recording is performed by the fringing fields emanating from the gap region between the write-poles of a conventional "ring"-type recording head. It is the geometry of a longitudinal ring-head that defines the upper limit of the write field of $2\pi M_S$, where $M_S$ is the saturation magnetization of the write-pole material. In perpendicular recording, write field is generated between the trailing pole of a single pole head and a soft underlayer (SUL), a soft magnetic material located below the recording layer. In such geometry, the upper limit of the write field is equal to $4\pi M_S$, which is two times higher than the highest field achievable with a longitudinal ring head.




(a) (b)

Figure 3. Diagram showing a side cross-section of (a) a typical perpendicular system including a SPH and a double-layer medium with a SUL and (b) a longitudinal system, including a ring-head and a single-layer recording medium.

Higher write efficiency of a perpendicular single-pole recording head in combination with a SUL can ba explained in greater detail as illustrated in Figure 4. It can be shown (the proof of this concept is beyond the scope of this paper [9]) that to evaluate the magnetic fields above the SUL boundary, the SUL can be thought of as a perfect magnetic mirror such that the magnetic field above the SUL boudnary is a superposition of the fields generated by both the magnetic elements above the SUL boundary and by their images located below the SUL boundary. This concept is illustrated in Figure 4, where the SUL is replaced with an image recording head. From this picture it is clear that in perpendicular recording the write process effectively occurs in the gap between the magnetic poles, the real and the image poles, which is in contrast to longitudinal recording where the writing is done by the frinding fields as outlined above. From simple superposition arguments, it is straighforward to show that the in-gap field is equal to $4\pi M_S$ while the highest value of the fringing field is equal to $2\pi M_S$.

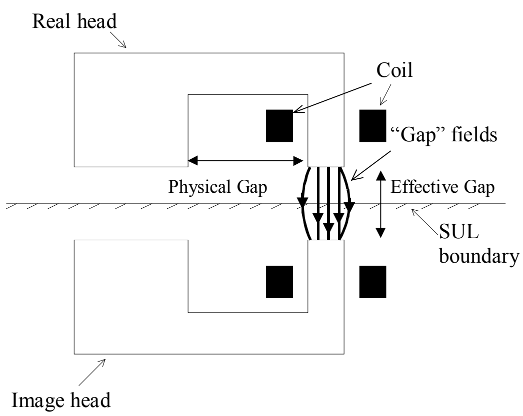



Figure 4 A schematic of the magnetic imaging principle in perpendicular recording using a medium with a soft underlayer.

As shown above, the maximum write field available in perpendicular recording is two times higher than the maximum write available in longitudinal recording. The direct consequence is the ability to write onto a higher anisotropy media (higher $K_U$). The use of higher anisotropy media materials allows higher areal densities without compromising the thermal stability of the recording data.

The spatial profile of the write field is also more beneficial for achieving higher areal density in perpendicular recording. The side gradients, i.e. the rate at which the field rolls off at the side edges of a recording head, are usually substantially sharper than what one observes in longitudinal recording. This property leads to better-defined tracks with a very narrow erase band. Along with better magnetic alignment of the media (see below), extremely narrow tracks are possible to achieve.

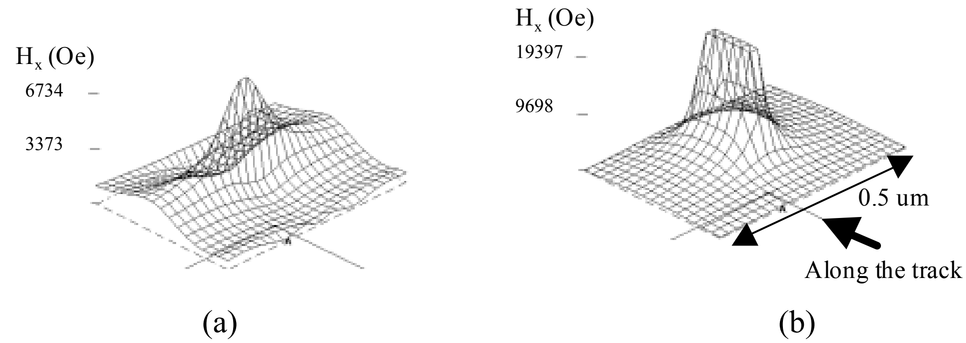



Figure 5. Longitudinal head field contours and perpendicular head field contours from (a) a longitudinal head with a 150 nm gap and (b) a perpendicular pole head with a pole thickness of 700 nm. The trackwidth is 50 nm in both cases.

The single pole perpendicular write heads used to acquire the experimental data presented in this paper, were made by focused ion-beam (FIB) modification of conventional longitudinal writers [11]. It should be emphasized that the main difference in the design of conventional perpendicular and longitudinal writers is the length of the gap between the magnetic write-poles. In terms of the write process, while in longitudinal recording the writing is done near the gap region, in perpendicular recording, the writing is done by the trailing edge of the trailing pole [12]. Figure 6 shows a state-of-the-art perpendicular recording head manufactured by FIB trimming of a conventional longitudinal write head by increasing the gap length and trimming the trailing pole and the reader to the specified dimensions. Both the trailing pole and the reader are designed for a 60nm track width.

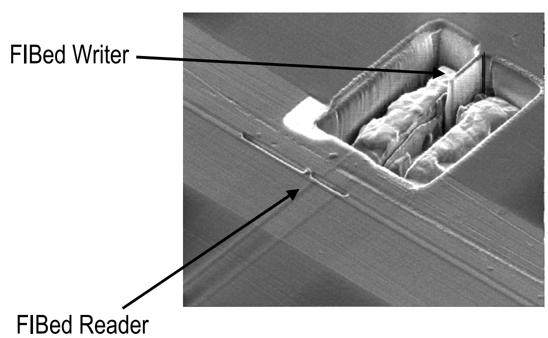



Figure 6. A single pole perpendicular write head made by focused ion-beam etching of a conventional longitudinal ring head. The trailing pole width is 60nm.

## 2.2 Well aligned media

In conventional longitudinal recording, the easy axes of individual grains are randomly oriented in the plane of a medium. (It should be recalled that the easy axis is the energetically favorable axis/direction along which the magnetization of a grain is aligned in the absence of external magnetic fields.) Thus, in longitudinal recording, a large fraction of the grains forming a bit has their easy axes severely misaligned with the bit magnetization direction. Writing well-defined bit transitions on such randomly oriented media imposes stringent requirements onto the spatial profile of a write-field. If one neglects the imperfections of a bit transition due to the granular nature of a medium, the quality of the bit transition is defined mainly by the write-field profile.

This is drastically different from perpendicular recording, in which the easy axis of each magnetic grain is relatively well aligned in the direction perpendicular to the plain of the medium. Thus, in a perpendicular recording, the magnetization direction of a recorded bit always coincides with the orientation of the easy axes of individual grains that form the bit. Well-defined easy axis orientation relaxes the stringent requirements for the trailing and side write-field gradients necessary to achieve sharp transitions, thus enabling the use of thicker media [10].

The intrinsically better alignment of perpendicular media helps record narrow tracks with well-defined transitions even into a relatively thick recording layer. A MFM image of two adjacent tracks with a 65 nm trackpitch written into a 50 nm thick CoCr recording layer using a 60 nm wide single pole head is shown in Figure 7 [7]. This is equivalent to a track density of ~400ktpi. It should be stressed that the state-of-the-art in longitudinal recording for the track density is ~100ktpi.

The possibility of using thicker recording layers further assists with improving thermal stability.

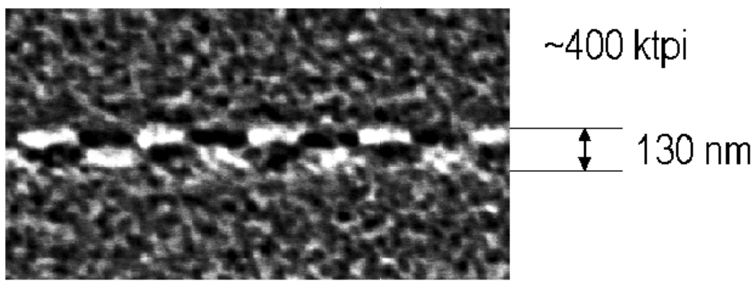



Figure 7. A MFM image of two tracks with a 65 nm trackpitch.

With respect to using well-aligned media, it should be remembered that previously it was shown that, although well-aligned perpendicular media might have a relatively small average angle between the magnetization and the perpendicular recording field, the torque created is still sufficiently large to quickly switch the magnetization [13, 14].

### 2.3 Absence of demagnetizing fields at bit transitions

One of the major destabilizing factors in longitudinal recording medium is strong demagnetizing field at the bit transition. The destabilizing influence of the demagnetizing field at the bit transitions is easy to see if one notices that the two adjacent bits of opposing magnetization directions repel in a similar way as two bar magnets with the poles of the same polarity, such as north-north or south-south, facing each other. The magnets would try to flip such that the poles of opposite polarities are next to each other. This is illustrated below in Figure 8.

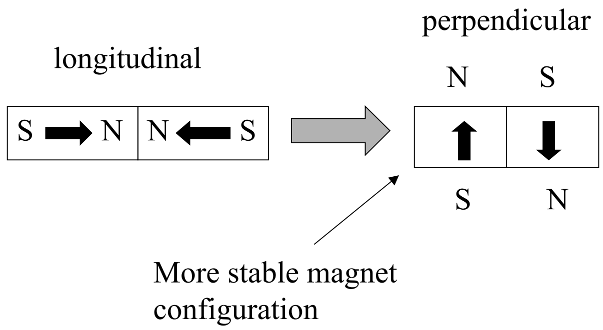
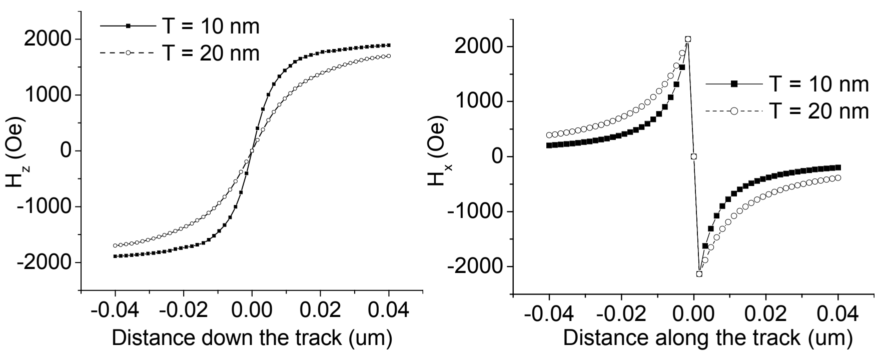



Figure 8. A schematic of the influence of demagnetizing fields in longitudinal and perpendicular media.

The calculated demagnetizing fields for the cases of longitudinal and perpendicular media for a single bit-transition are shown in Figure 9. In the longitudinal recording, high demagnetizing fields at bit-transitions destabilize individual grains leading to a finite transition width. This is opposite to perpendicular recording, in which the demagnetizing fields reach their minima at the bit-transitions, thus promoting ultra-narrow transitions and, consequently, high-density recording.

It can also be noticed that, unlike in longitudinal recording, the demagnetization fields in perpendicular recording decrease as the thickness increases, thus promoting thicker recording layers, which in turn is beneficial for the thermal stability. In this respect, it is common to notice that although perpendicular recording promotes high densities, the stronger influence of the demagnetization fields at lower densities is a disadvantage of perpendicular recording.




(a) (b)

Figure 9. The demagnetization field versus the distance down the track along the central planes of 10 nm and 20 nm thick recording layers for (a) perpendicular and (b) longitudinal recording media.

## 3 A new system component: soft underlayer challenges and design considerations

One of the key aspects of perpendicular recording that makes it superior to the longitudinal recording with respect to superparamagnetic effects is utilization of media with a SUL. A single-pole head and a medium with a SUL perpendicular recording system enables write fields in excess of 80% of $4\pi M_S$ of the pole head/SUL material. This doubles the fields available in longitudinal recording, thus opening the possibility to write on substantially higher anisotropy media and leading to better thermal stability. Acting as a magnetic mirror, SUL effectively doubles the recording layer thickness, facilitating substantially stronger readout signals. Also, the effective thickness increase due to the mirroring effects by a SUL leads to the reduction of the demagnetizing fields with a potential to further improve thermal stability.

While the utilization of perpendicular media with a SUL should make it possible to postpone the superparamagnetic limit, the SUL introduces a number of technical challenges. Some of the issues related to the presence of the SUL are discussed below.

### 3.1 SUL as a major source of noise

Among the technical challenges introduced by the presence of a SUL is the fact that a not properly optimized SUL material can introduce a significant amount of noise into the playback signal. The noise results from the stray field generated by the effective charges resulting from domain walls in the SUL as illustrated in Figure 10.

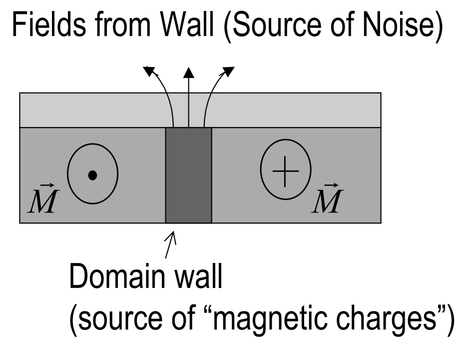



Figure 10. A schematic of the stray fields generated by a SUL

Magnetic biasing of the SUL, i.e. forcing the SUL into a single magnetic domain state, allows to minimize the SUL noise. The biasing can be achieved either by application of an external magnetic field or by engineering a SUL material with a built-in biasing field. Figure 11 shows a schematic of the experimental setup to study the effect of magnetic biasing of the SUL on the noise. The magnetic biasing was achieved using two NdFeB permanent magnets placed in the vicinity of the media. The placement of the magnets was such that it allowed achieving complete saturation of the SUL underneath the reader. Special care was necessary to arrange the magnets sufficiently far from the recording head ~2cm away in order not to affect the properties of the read element.

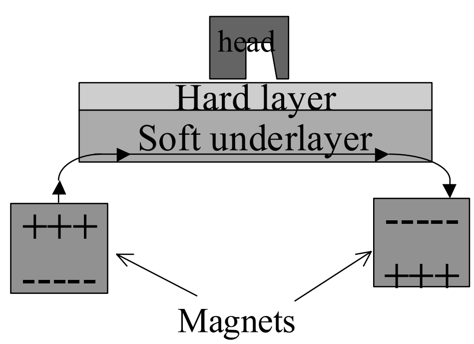
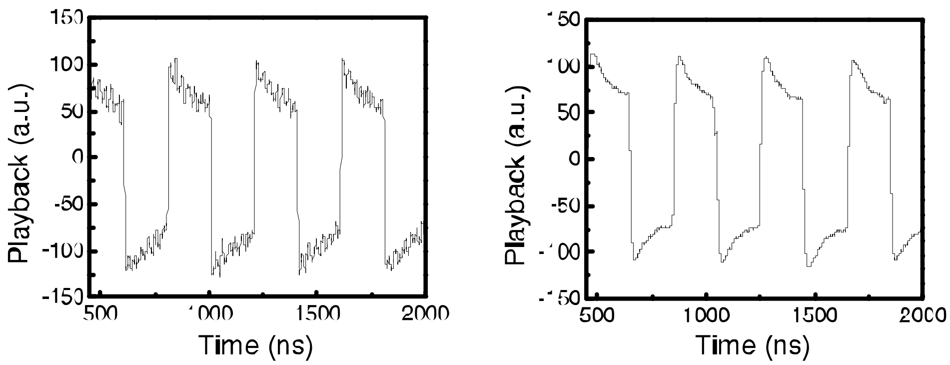



Figure 11. A schematic of experimental setup to magnetically bias SUL film.

Figure 12 shows the playback signals from the two media with as deposited non-biased (a) and magnetically biased (b) SUL's. A substantial level of noise attributed to presence of a large number of domain walls (confirmed by magnetic force microscopy) in the SUL can be seen in Figure 12a. A drastic reduction of the noise (by at least 10dB) is clearly observed in Figure 12b where the SUL is magnetically biased.




(a) (b)

Figure 12. Playback signal from two media with different SUL's. (a) SUL with a large number of stripe domains. The presence of stripe domains was confirmed using magnetic force microscopy. (b) Biased SUL with domain walls swept out from the SUL material.

The magnetic biasing saturates SUL film forcing it into a pseudo-single domain state effectively sweeping the domain walls out of the SUL material. This results in elimination of the SUL noise.

### 3.2 SUL magnetic moment

To properly design a perpendicular recording system that utilizes a medium with a SUL, it is critical to choose an appropriate SUL material. As illustrated in Figure 13, if the magnetic moment of a SUL material is lower than the magnetic moment of the recording pole tip, saturation of the SUL underneath the pole tip can occur.

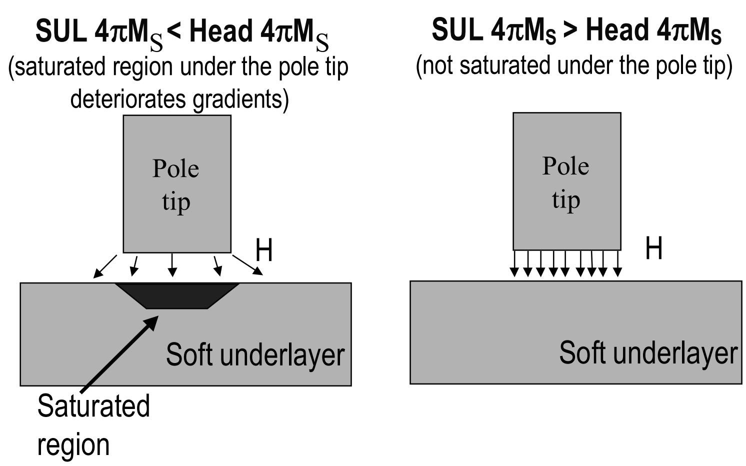



Figure 13. A schematic illustrating the saturation effect in the SUL is the magnetic moment of a SUL is lower than the magnetic moment of the write pole tip.

The results of boundary element modeling for two different head/SUL combinations are presented in Figure 14. It can be noticed that it is possible to generate strong recording fields with the magnitude approaching $4\pi M_S$ of the pole tip even if the SUL has a lower magnetic moment than the pole tip. However, saturation of the SUL will lead to a substantial deterioration of the trailing field gradients. The trailing gradients in the case of the Permalloy based SUL are substantially worse than the trailing gradients in the case when a FeAlN based SUL is used.

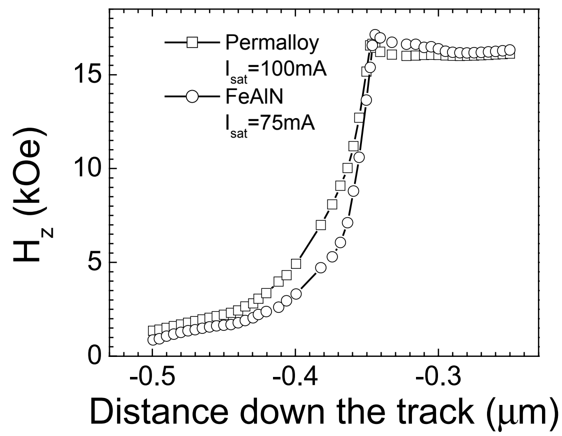



Figure 14. Trailing fields from a single pole perpendicular write head made out of FeAlN ($4\pi M_S$ =20kG) for FeAlN and Permalloy ($4\pi M_S$ =10kG) SUL's.

It follows that if high moment materials are used for write heads, e.g. CoFeB, FeAlN, etc., the moment of the SUL material should match or exceed the moment of the pole tip material.

### 3.3 SUL thickness

Another important issue related to the optimized design of a SUL is the SUL thickness. Using simple considerations of magnetic flux conservation, the minimum thickness required for the SUL to function properly is given by

$$t_{\text{soft underlayer}} \geq \frac{1}{2} \frac{M_{\text{S pole tip}}}{M_{\text{S soft underlayer}}} w_{\text{pole tip}},$$

where the $w_{\text{pole tip}}$ is the width of the write pole tip, i.e. the dimension of the write pole tip defining the track width. The evaluation of the above equation for the case of 100Gbit/in$^2$ areal density and 4:1 bit aspect ratio, i.e. a 160nm wide pole tip, and the same pole tip and SUL materials, gives the lower boundary on the SUL thickness of 80nm. It should be stressed that this thickness is substantially smaller than the minimum required thickness often quoted in the literature of hundreds of nanometers to several microns.

This important observation needs to be strongly emphasized. Due to materials properties, the mentioned above problem of SUL noise becomes increasingly aggravated with the increasing thickness of the SUL.

### 3.4 SUL influence on the resolution of a perpendicular recording system

An additional challenge that the presence of a SUL imposes is potential deterioration of the system resolution. During reading from a medium with a SUL, due to the magnetic imaging properties of the SUL, the resolution can get distorted if the separation between the ABS and the SUL (sum of the recording layer thickness and the flying height) is comparable to the reader thickness.

This phenomenon is clearly illustrated in the calculated [15] PW50 and the playback signal versus the underlayer to the ABS distance, shown in Figure 15. PW50 is the physical width of a single transition, the measure of the spatial resolution of a recording system. In these calculations, a fixed recording layer thickness of 10 nm was assumed, and spacing between the bottom side of the recording layer and the underlayer was varied from zero to some finite values. For comparison, the dotted straight lines indicate the values for the case when there is no underlayer. It can be clearly seen that the resolution of the modeled recording system substantially deteriorates at certain values of the ABS-to-SUL spacing. This suggests that a special care has to be taken to properly optimize the system's resolution.

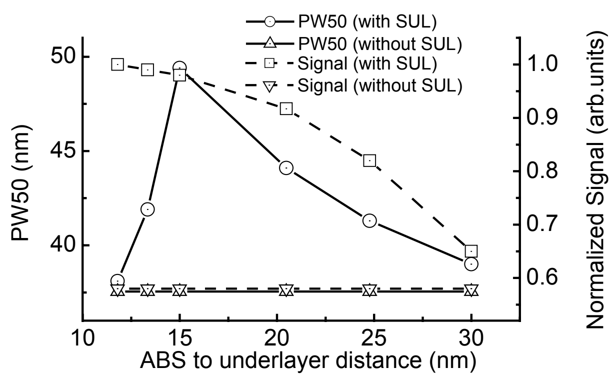



Figure 15. PW50 and the normalized playback vs. the ABS to underlayer spacing. 30 nm GMR element and a 70 nm shield-to-shield spacing are assumed.

Although, in a properly designed system this resolution distortion can be almost completely eliminated, it causes the resolution of a typical read head in a system with an underlayer to be at most as good as the resolution of an equivalent head in a system without an underlayer. It should be noted, however, the underlayer definitely increases the playback signal, which is desirable at high areal densities.

## 4 Playback: new signal processing schemes

One of the drastic differences between perpendicular and longitudinal recording is the difference in playback signals. To help understand the basic difference in the playback process between longitudinal and perpendicular recording, schematic diagrams of the stray fields emanating from a longitudinal medium and perpendicular media without and with a SUL are shown in Figure 16, respectively. As can be noticed, in the longitudinal case, the stray fields emanate only from the transitions, with the fields near the transitions oriented perpendicular to the disk plane. On the contrary, in the perpendicular cases, the stray field emanates from the effective magnetic "charges" at the top and effective (due to a SUL) bottom surfaces of the recording layer, with the field near the transitions oriented parallel to the disk plane.

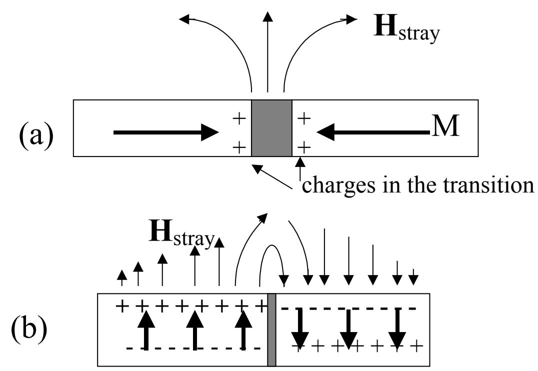



Figure 16. Diagrams showing the sources of stray fields in the case of (a) longitudinal recording, and (b) perpendicular recording.

As a result of the different magnetic "charge" distributions, the playback waveform differ drastically between longitudinal and perpendicular recording schemes. It is illustrated in Figure 17 where typical low-density playback waveforms are shown for both perpendicular and longitudinal recording.

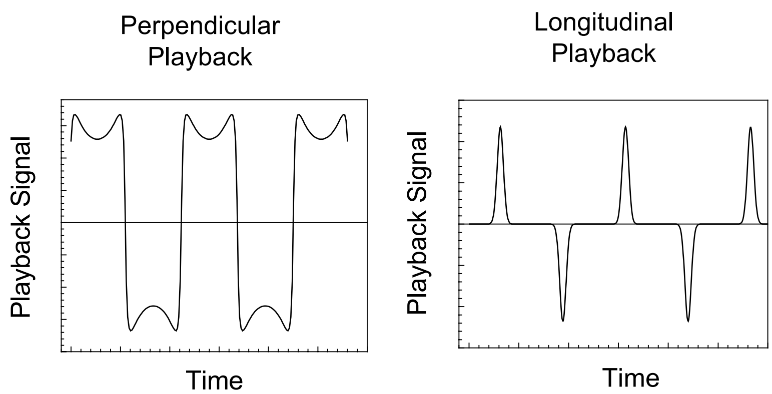



Figure 17. Typical playback waveforms for perpendicular and longitudinal recording schemes.

The shown above waveforms for perpendicular and longitudinal recording schemes outline major difference between perpendicular and longitudinal recording. While in longitudinal recording the signal is present only at bit transitions, in perpendicular recording the signal is read not only from a bit transition but also from across the whole bit area. It is possible to differentiate the perpendicular playback signal to make it similar to the playback signal in longitudinal recording. However, it should be remembered that differentiate perpendicular playback is only similar but not identical to longitudinal playback. The difference arises in the absence of a transition when a longitudinal playback signal is equal to zero while a differentiated perpendicular playback is, although relatively small in amplitude, but is still finite.

It should be stressed that while not entirely suited to be processed by conventional longitudinal channels, perpendicular playback clearly contain more information than typical longitudinal waveforms, in which the signal arrives only from transitions. This property could potentially be used to advantage in future channel designs.

## 5 New materials challenges

While the requirements for the head materials used in perpendicular recording are similar to the head materials used in longitudinal recording, the major differences exist with respect to media materials. A typical perpendicular medium consists of two magnetically active layers: a hard layer and a SUL (See Figure 18). A hard layer in a perpendicular medium has rather different magnetic properties from a hard layer utilized in conventional longitudinal recording. It should also be noted that there is no analog to a SUL in longitudinal recording. The requirements for these two layers are outlined below.

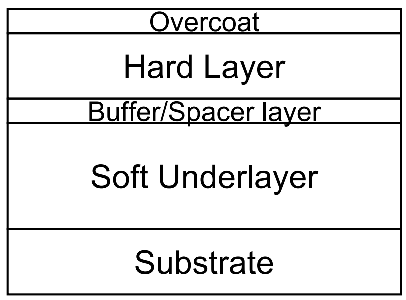



Figure 18. A schematics of a typical perpendicular medium.

### 5.1 Hard layer materials

The primary approach to the design of a perpendicular recording layer is in many ways similar to the design of a conventional longitudinal recording layer. All the media in use today has granular structure, i.e. made of polycrystalline materials. Major goals inherent to both longitudinal and perpendicular recording layer development are small grain size, small grain size distribution, texture control, optimization of the inter-granular exchange de-coupling, etc.

A large variety of today's perpendicular magnetic recording layer types can be clearly divided into the two major categories: 1) Alloy based media, such as CoCr-alloys[16, 17], and 2) media based on magnetic multilayers, such as Co/Pt, Co/Pd or others[18, 19]. Figure 19 contrasts the major difference between alloy and multilayer media. In alloy media, the magnetic anisotropy is controlled by magnetic crystalline anisotropy. The alloy media are usually highly textured to insure well-defined magnetic easy axis [20]. In magnetic multilayers, the magnetic anisotropy is controlled by interfacial effects between a magnetic layer, such as Co, and a highly polarizable spacer layer, such as Palladium or Platinum. In contrast to alloy media, this set of materials as used in perpendicular media usually possesses a very weak texture.

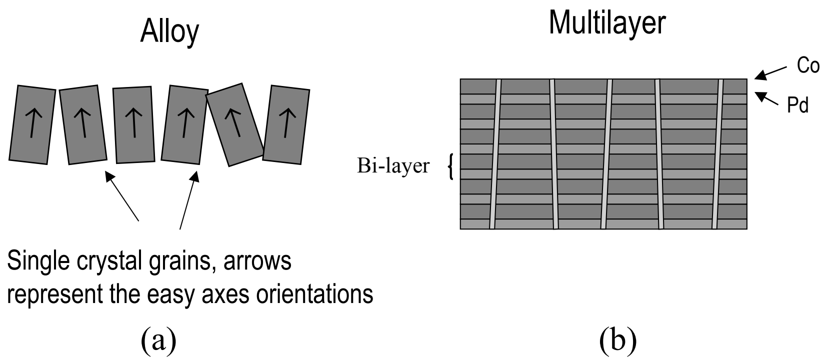
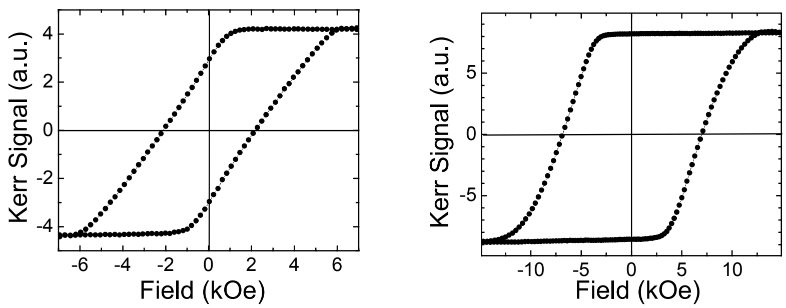



Figure 19. A schematic representation of major microstructural differences

Material-wise, perpendicular CoCr-based alloy recording layers are similar to conventional longitudinal CoCr-based media, with the major difference being the orientation of the magnetic easy axis. Therefore, a significant amount of information accumulated in the course of the longitudinal media development can be used to control the critical parameters such as the grain size and the inter-granular exchange coupling. At the same time, CoCr-based perpendicular media have some open issues. For example, it is not clear yet if it is possible to make a CoCr-based medium with sufficiently high anisotropy to avoid superparamagnetic instabilities at ultra-high areal densities. It also has proven to be difficult to make CoCr-alloy based perpendicular recording layers with a remanent squareness of 1. The remanent squareness is defined as a ratio between the remanent magnetization, the value of magnetization on a M-H loop at H=0, and the saturation magnetization, the maximum value of magnetization. It is believed that a remanent squareness of 1 is necessary for low-density bit pattern stability. Also, a remanent squareness of less than 1 can lead to substantial amounts of DC noise. Various magnetic alloys such as L10 phases of FePt, CoPt, etc. are being studied as higher anisotropy alternatives for the recording layer.

The magnetic multilayer based recording layers typically have significantly larger anisotropy energies (Coercive fields of above 15 kOe have been reported.) and are thus promising to be extendable to significantly higher recording densities. Another advantage of the magnetic multilayers is the fact that typically these materials have a remanent squareness of 1.

To compare basic magnetic properties of CoCr-alloy and mutlilayer based recording layers, typical M-H loops by a Kerr magnetometer for a 50 nm thick perpendicular CoCr thin-film and a 52 nm thick Co/Pd structure (a stack of 40 sets of adjacent 3 and 10 Angstrom thick layers of Co and Pd, respectively) are shown in Figure 20a and b, respectively. It can be noticed that in addition to the remanent squareness of 1, the Co/Pd structure exhibits nucleation fields in excess of 3kOe, a useful characteristic to avoid data self-erasure due to stray fields. Meanwhile, the CoCr material shown in Figure 20a has a squareness of 0.75. The CoCr and Co/Pd recording layers have coercive fields and magnetizations of approximately 3 kOe and 9 kOe and 300 emu/cc and 200 emu/cc, respectively.




(a) (b)

Figure 20. An M-H loop of a 50nm thick (a) CoCr-alloy layer and (b) Co/Pd multilayer.

The direct consequence of remanent squareness less than 1 is shown in Figure 21, which compares the spectral SNR distributions for the two media types. The CoCr medium exhibits a significant amount of noise at lower linear densities. This is mainly due to the fact that the dominant contribution to the noise at low linear density in the CoCr-based medium comes from the DC noise which results from the relatively low value of remanent squareness, as described below in more detail.

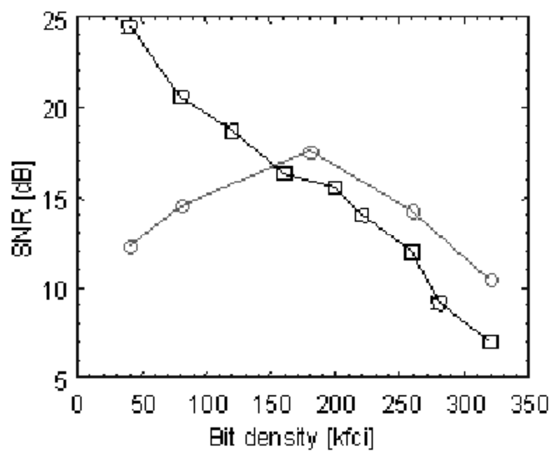



Figure 21. SNR versus the linear density for a CoCr-alloy (hollow circles) and a Co/Pd multilayer (hollow squares).

## 5.2 High anisotropy SUL materials

Several design guidelines for SUL's were discussed above including thickness requirement and magnetic moment requirement. An additional parameter, which is critical to achieve optimized performance of a SUL in a perpendicular recording system, is magnetic anisotropy of the SUL material. The dynamic properties [21, 22] and influence of a SUL on system's resolution [23] are affected by the value of the anisotropy field. The latter is illustrated in Figure 22, where the playback versus the linear density (roll-off) curves are shown for identical perpendicular recording systems with different SUL materials. The explanation of the quantum-mechanical nature of this effect is beyond the scope of this paper. However, it should be mentioned that the deterioration of the system's resolution arises from inability of lower anisotropy SUL materials to perfectly respond to spatially-fast varying magnetization patterns in the recording layer.

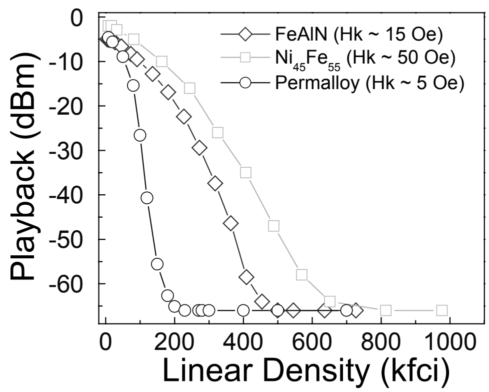



Figure 22. Playback roll-off curves for perpendicular recording media with identical recording layer but different SUL's. The extent of the roll-off curves to higher linear densities for higher anisotropy SUL indicates the advantage of using high anisotropy SUL materials.

## 6 How far perpendicular recording will take us and what will come next?

It should be emphasized that although perpendicular recording allows to surpass the superparamagnetic limit of longitudinal recording, there exists a superparamagnetic limit native to perpendicular recording as well. A number of factors such as the availability of higher write fields, possibility of using thicker well-aligned media, and the absence of demagnetizing fields at bit transitions aid in promoting thermally stable media to substantially higher areal densities. However, it has been shown that with all factors taken into account, the maximum areal density achievable with perpendicular recording scheme in development today is 500-1000 Gbit/in$^2$ [5,24,25]. Once the perpendicular magnetic recording reaches its superparamagnetic limit, a new wave of technological innovations will have to take place.

As mentioned in the beginning of this text, the foremost fundamental reason for the existence of the superparamagnetic limit is the head materials constraint imposing the limitation on the available head field that limits the utilization of higher anisotropy media. Among the potential successors of perpendicular recording is heat-assisted magnetic recording (HAMR) [26], in which the anisotropy of a recording medium is temporarily reduced during the write process. In HAMR schemes, an additional element to be incorporated in the design of a recording system is a source of heat (envisioned as an ultra-small light source) to locally increase the temperature of the recording medium. The increase of the medium temperature leads to the decrease of the medium coercivity enabling the writing with relatively small magnetic fields.

Additionally, patterned media can be utilized to further extend the limits of magnetic recording [26]. In a patterned medium, the location and the size of the magnetic features are pre-determined by the medium manufacturing process. Elimination of the element of randomness characteristic to today's polycrystalline recording media is a clear advantage of the patterned medium approach. However, for such a medium to become a serious contender to replace conventional alloy or multilayer media, an economically viable manufacturing process will have to be developed [27,28].

It should be emphasized that due to the advantageous nature of perpendicular recording in promoting extremely high areal bit densities (high write field amplitude, well aligned medium, sharp field gradients, absence of demagnetizing field at transitions, etc.), the future technologies such as mentioned above HAMR and recording on a patterned medium, are likely to be developed as extensions of perpendicular magnetic recording schemes [26] rather than to be based on conventional longitudinal recording.

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