



Tunneling magnetoresistive devices as read heads in hard disk drives

Bor-Yuan Jiang, Kunliang Zhang, Takahiko Machita, Wenyu Chen, Moris Dovek^{*}

Headway Technologies, a TDK Group Company, 682 S. Hillview Dr, Milpitas, CA 95035, USA

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ABSTRACT

Hard Disk Drive read heads moved from GMR to Tunneling Magnetoresistive (TMR) Devices as a way to enhance head SNR in order to keep up with advanced linear densities. TMR technology was further extended by the transition from amorphous alumina tunneling barriers to crystalline MgO barriers lattice matched to adjacent BCC magnetic layers resulting in much higher MR ratios. Enhanced side shielding using Junction Shield and reduced shield to shield spacing were additional enablers that increased track and linear density capabilities of TMR heads. TMR heads gained additional momentum and complexity by the introduction of two dimensional recording heads that boosted head SNR by up to 3 dB. As the RA of the tunneling barriers is reduced, overcoming spin torque noise presents itself as a further challenge to be addressed. As device dimensions are scaled down, magnetic thermal noise can only be overcome by increasing the moment of the free layer which may already start establishing the final density point achievable by TMR heads.

1. Introduction

For reading recorded information, Hard Disk Drives (HDD) have used read heads that have been decoupled from write heads starting with the migration to AMR (anisotropic magnetoresistance) [1]. While this transition has allowed an independent design of the read head alongside the write heads as compared to earlier inductive heads where the two functions were combined on the same transducer, read heads still face the need to keep up with dimensional requirements corresponding to each areal density (AD) as well as maintaining adequate readback signal amplitude and signal to noise ratio (SNR) with ever shrinking device size. In order to meet the challenge to maintain head SNR at narrowing dimensions, the recording industry transitioned from Giant Magnetoresistive (GMR) heads to Tunneling (TMR) heads around 2006. The transition to TMR heads contributed to the acceleration of the compounded AD growth rate (CGR) from around 25 % the year prior to around 60 % for the subsequent few years [2].

GMR Heads, also known as Spin Valve Heads, relied on a sense current that was conducted in the plane of the wafer, in other words, in the cross track direction. The readback amplitude was proportional to the sense current times the sensor resistance change in response to the field from the recording media. TMR heads, on the other hand, were exclusively designed as CPP (current perpendicular to plane) devices conducting the sense current downtrack. The signal amplitude remains proportional to the sense current times the media field induced resistance change.

The transition from current-in-plane (CIP) GMR to TMR was largely driven by the need to maintain performance while scaling down the size of the device. In order to maintain the AD growth rate, the physical dimensions of the sensor must keep on reducing to match the ever shrinking size of the bit. This led to several technical difficulties in maintaining the SNR for CIP GMR [2]. First, the need for insulation between the shields and the sensor prevented efficient read gap reduction, which is critical for achieving narrower pulse width. In addition, the contact resistance from the device leads increased as the sensor height SH was reduced, leading to higher Johnson noise. Perhaps most critically, the signal voltage was dependent on the sensor size and decreased for a narrower sensor. Consider a square-shaped sensor with a height SH equal to its track width TW , while having a small fixed thickness $t \sim 10$ nm. The GMR signal voltage is given by $MR \times I \times R \times u$, where MR is the magnetoresistance ratio, I is the sense current through the sensor, R is the sensor resistance, and u is the percentage utilization of MR (determined mainly by the total effective bias on the sensor and the strength of the media field). As the sensor size decreases $R = R_{\text{sheet}} \times TW/SH$ remains constant so that Johnson noise is the same. However the current I has to be reduced along with the sensor height SH to prevent increased Joule heating, leading to a reduction in the signal voltage.

On the other hand, the CPP geometry of TMR naturally avoids issues with lead resistance and read gap. The shields are now the leads and can be in electrical contact with the sensor. TMR heads also boast higher MR ratios than GMR [3,4]. Unlike GMR, the TMR signal voltage, given by $MR \times V_{\text{bias}} \times u$, can remain constant as the sensor size shrinks. The shot

^{*} Corresponding author.

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noise (with power $\propto V_{bias} \times R$ [5]) is however a concern as the MTJ resistance increases with decreasing sensor area A , requiring continual reduction of RA , defined as the product of sensor resistance and lateral sensor area. This is increasingly difficult today as RA reduction is usually achieved by reducing the thickness of the tunneling barrier, which is already at ~ 0.8 nm or less.

In both GMR and TMR, the SNR scales linearly as the lateral dimensions of the sensor. Around 2006, an estimated signal voltage for GMR was ~ 6 mV (assuming $MR = 13\%$, $I = 3$ mA, $R = 40 \Omega$, $u = 40\%$), while the Johnson noise voltage was $\sqrt{4k_B TRW} \approx 18 \mu V$ (at temperature $T = 300$ K and bandwidth $W = 0.5$ GHz), yielding a head SNR of 51 dB. In comparison, the shot noise voltage for TMR is $\sqrt{2eV_{bias}RW} \approx 85 \mu V$ (at $V_{bias} = 150$ mV, $RA = 3 \Omega \mu m^2$, and $A = 0.01 \mu m^2$), so that a significantly higher $MR = 50\%$ and signal voltage of 29 mV would be needed to maintain the same level of SNR in theory. However, real TMR heads with comparable SNR to GMR devices were fabricated even at similar MR , as shown for example in [6]. This was attributed to the presence of pinholes in the tunnel junction [7] which led to a significantly lower measured electronic noise than theoretical predictions. In addition, very high MR ratios greater than 100 % have already been demonstrated with crystalline MgO barriers [8,9], albeit at a much larger barrier thickness and RA . There was, hence, a clear direction forward for TMR, namely the implementation of high MR and low RA barriers into real devices, whereas GMR had no real extendibility into smaller sensor dimensions.

2. TMR film evolution

TMR devices have relied on a high readback signal amplitude to displace GMR technology; and the push has therefore been towards higher TMR ratios. Following the discovery of a high TMR ratio of about 12 % in magnetic tunnel junctions (MTJs) using Al oxide barrier and conventional 3d ferromagnetic metals or alloys from Fe, Co, and Ni at room temperature [10] MTJ based TMR read heads have generated lots of interests and have promised significant AD growth in HDDs [11,12]. It became quickly apparent that the target was to fabricate a good MTJ with a large TMR ratio and a low RA ; and therefore, the quality of the barrier was considered crucial. Plasma oxidation typically produces high quality barriers due to more thorough oxidation; however, it typically associates with higher RA range. For lower RA , radical shower or natural oxidation yields much better results due to a lower chance to induce over oxidation. After nearly a decade of extensive engineering work, the MR ratio on Al oxide barriers remained limited at around 70 % [13]; and this severely could have limited the feasibility and AD extendibility of TMR heads and other spintronic devices. A new barrier would overcome this limitation.

Alumina tunnel barriers are amorphous. However the magnetic materials just below barrier (AP1, also known as reference layer) and above barrier known as free layer (FL) typically exhibit certain crystalline structure, especially after magnetic annealing. The structural mismatch between AP1 and FL has mitigated the tunneling spin polarization (TSP) of the magnetic layers, hence limited achievable TMR ratio. Mavropoulos et al. suggested that crystalline tunnel barriers may give rise to much higher TSP and MR values because of a highly spin-dependent evanescent decay of certain wave-functions, with particular transverse momentum values, across the tunnel barrier [14]. Almost simultaneously, Butler et al. and Mathon et al. predicted that fully ordered (001) oriented Fe/MgO/Fe MTJs could achieve TMR ratios of 100 % to even 1000 % for a sufficiently thick MgO barrier [15,16] and that the TMR ratios of body centered cubic Co(001)/MgO(001)/Co(001) and the FeCo(001)/MgO(001)/FeCo(001) systems were predicted to provide several times greater MR ratios compared to those predicted for the Fe/MgO/Fe system [17]. The origin of this giant TMR effect is understood as coherent spin-polarized tunneling, where the symmetry of electron wave functions plays a crucial role (see Fig. 1).

Additional novel ideas laid the foundation of subsequent

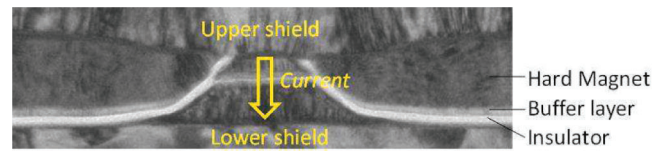


Fig. 1. ABS TEM image of a basic TMR Read Head.

experimental works. In 2004, Yuasa et al. demonstrated giant TMR ratios of up to 180 % in single-crystal Fe/MgO/Fe MTJs deposited by MBE [18,9]. Parkin et al. showed 220 % in highly oriented (001) CoFe/MgO/CoFe MTJs within the same year, and demonstrated that high TSP can be preserved with crystalline MgO barriers. [19]. In particular, Djavapwira et al. obtained 230 % TMR with sputtered CoFeB/MgO/CoFeB MTJs. Their results are of significant technology importance for the magnetic recording head industry because they deposited MTJs with standard spin-valve structure technology performed at room temperature. They used a conventional sputtering method instead of an MBE system; and they achieved a giant TMR ratio with simple amorphous CoFeB ferromagnetic electrodes, instead of strenuously high temperature deposition with single crystal structures. [20]. Their work made the technology transition from Al₂O₃ to MgO barrier much easier thanks to the use of simple CoFeB amorphous magnetic electrodes to preserve MgO structure from being impacted by FCC underlayers and free layer structures. Upon annealing CoFeB and MgO can be crystallized to BCC structures. After demonstrating superior performance compared to Al₂O₃ TMR as shown in Fig. 2, MgO TMR became the state-of-art technology for all future spintronic devices including HDD recording read heads.

3. Advanced TMR device structures

3.1. Extendibility of TMR for side shielding

For higher TPI (Tracks Per Inch) environments, narrower read widths with less side reading provide a key improvement opportunity to obtain high signal resolution at higher track densities. Side reading is evaluated by MTS (Micro Track Sharpness), given by the ratio of MT10 and MT50 as illustrated in Fig. 3. Towards this goal, a new structure of readers with side shields was proposed, called “Junction shield (JS)” [21–23].

JS has soft magnetic materials that apply a uniform longitudinal field on the free layer (FL) compared to the hard magnetic materials previously used. The soft magnetic materials are magnetically coupled with the upper shield which is weakly pinned by a top antiferromagnetic layer, allowing absorption of the flux nearby from other bits. The soft magnetic layers serve as both bias layers and side shield concurrently in this structure (See Fig. 4).

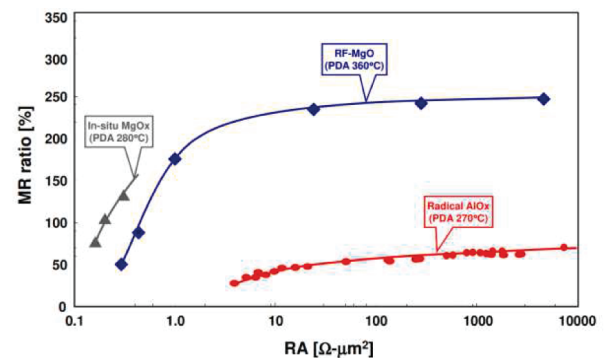


Fig. 2. TMR vs RA trend for various MTJs (MgO barrier vs AlOx barrier) (courtesy of Canon Anelva).

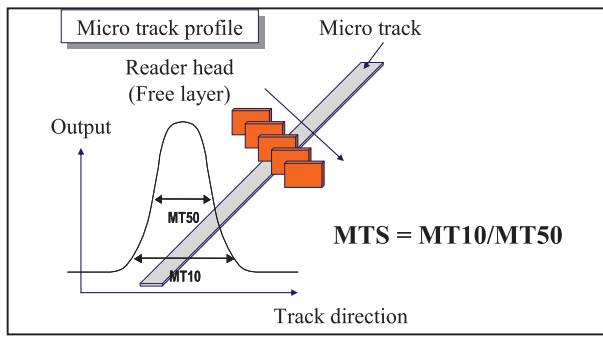


Fig. 3. Definition of MTS: A previously prepared micro track is scanned across a reader element. The mid-point and 10 % of the resulting track profile is captured.

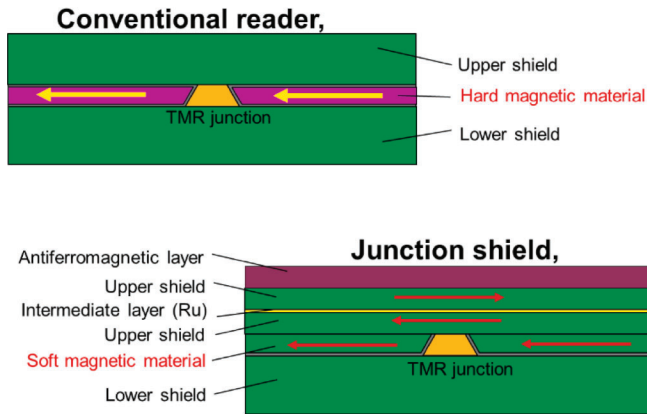


Fig. 4. Schematic image comparison between the hard biased reader and the JS biased reader.

JS biased readers have narrower MT50 and MT10, as well as smaller MTS under the same physical track width (TW). In addition, the gain becomes larger as the physical track width is narrowed, which allows us to achieve higher TPI using the same physical track width and similar TMR junction electrical resistance (See Fig. 5).

JS biased readers also have significantly smaller Asymmetry sigma, given by the standard deviation of the normalized difference between Amplitude at positive peak field and one at negative peak field on a number of tested devices. This is illustrated in Fig. 6 (a) as measured under the same average amplitude group of devices. FMR frequency corresponding to FL, given by $f_0 = \frac{\gamma}{2\pi} (M_s \times H_{stiff})$, is used to understand how much longitudinal field is applied on the free layer. In this equation, M_s is the saturation magnetization of the free layer, γ is the gyromagnetic ratio, and H_{stiff} is the longitudinal field acting on the free layer. FMR frequency corresponding to the free layer of JS biased readers shows smaller sigma under the same mean, indicating a more uniform and consistent bias field acting on the free layers of a group of devices demonstrating a better bias function (Fig. 6(c)).

In short, JS has a significant improvement on the side reading reduction with a better bias function for higher TPI over the

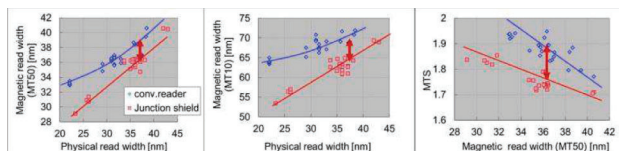


Fig. 5. Experimental results of MT10, MT50 and MTS from spin-stand dynamic performance measurement.

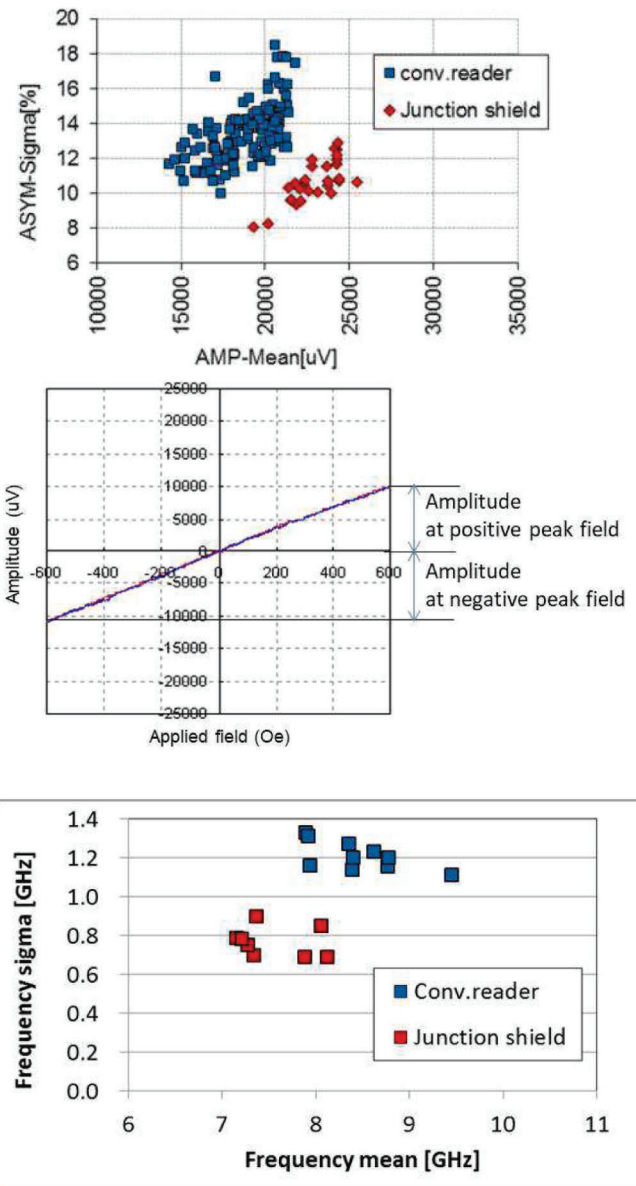


Fig. 6. Experimental results of QST(Quasi Static Test) and FMR(Ferro Magnetic Resonance): (a) asymmetry std dev vs amplitude—each data point representing a batch of reader from a range of designs (b) Definition of asymmetry of each read element (c) FMR resonance mean and sigma—each data point representing a batch of reader from a range of designs.

conventional reader and thus became a standard design in the HDD industry.

3.2. Read gap reduction

To achieve higher BPI(Bits Per Inch), the shield-to-shield (S-to-S) spacing reduction is a key enabler to obtain high signal resolution towards a higher linear density. In order to achieve such higher BPI, a new design concept was introduced by recessing the antiferromagnetic (AFM) layer from the ABS, called “Recessed Pin Layer (RPL)” structure [24]. This design is compatible with the Junction Shield; thus both benefits of side reading reduction for higher TPI and high signal resolution for higher BPI can be realized.

As illustrated in Fig. 7, RPL has no AFM layer at the ABS(Air Bearing Surface). AFM is recessed from ABS and an additional shield layer replaces the AFM layer under the reference layer (AP1) via a nonmagnetic

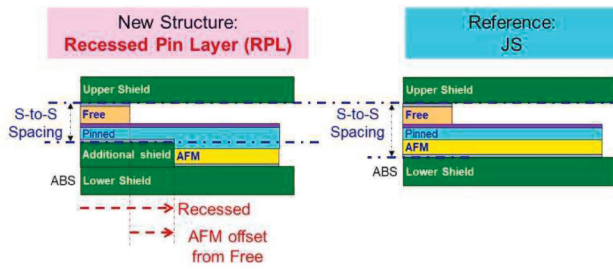


Fig. 7. Cross-sectional schematic diagram of the new reader with RPL and JS as a reference.

buffer layer near ABS. This structure allows reduction of the S-to-S spacing significantly below 20 nm. Fig. 8 shows ABS and cross sectional TEM images as an example of this RPL concept. The S to S spacing could be as low as 20 nm and the JS bias is still clearly present in the device.

RPL has higher Resolution under similar Amplitude (TAAL) compared with the JS by + 3 ~ 4 percentage points, which primarily results from the 5 nm narrower S-to-S spacing realized by the structure (See Fig. 9(a)). The resolution is a ratio of signal amplitude (TAAM) at high frequency (2 T) to one measured (TAAL) at low frequency (6 T). In addition, the device has smaller MTS under the same MT50 compared with the earlier JS readers by around 0.04 (See Fig. 9(b)). The higher resolution and smaller MTS come from better magnetic shielding experienced by adjacent bits on media as a result of the narrower S-to-S spacing.

Fig. 10 shows the ESD profiles of the RPL and the conventional reader. In the conventional design, fluctuation of resistance was observed just before reaching a breakdown voltage of more than 0.5 V. On the other hand, no clear fluctuation of resistance was observed in the RPL. It implies that magnetization in pinned layer is stable even just before breakdown during which high bias current flows through TMR film. It suggests that the recessed AFM structure has robustness against bias current induced instability of the pinning strength.

RPL has a significant improvement on the resolution for higher BPI and also on the MTS for higher TPI even when compared with simple JS as a reference reader. Additionally, it demonstrates superior stability. Therefore, RPL provides an attractive solution towards future generations of data center usage of HDDs as illustrated in Fig. 11 which simultaneously requires high performance and high reliability.

4. Extendibility to dual TMR elements

Wood et al. [25] proposed a two dimensional writing method where cross track coding and detection schemes would emulate the elaborate detection schemes used on sequential downtrack data in high density recording. This method relied on shingle recording for preparation of

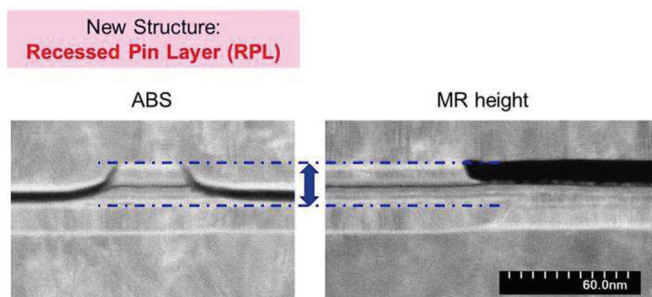


Fig. 8. ABS and cross-sectional TEM image of the new concept reader with RPL. Shield to Shield Spacing shown with the blue arrow is 20 nm demonstrating extendibility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

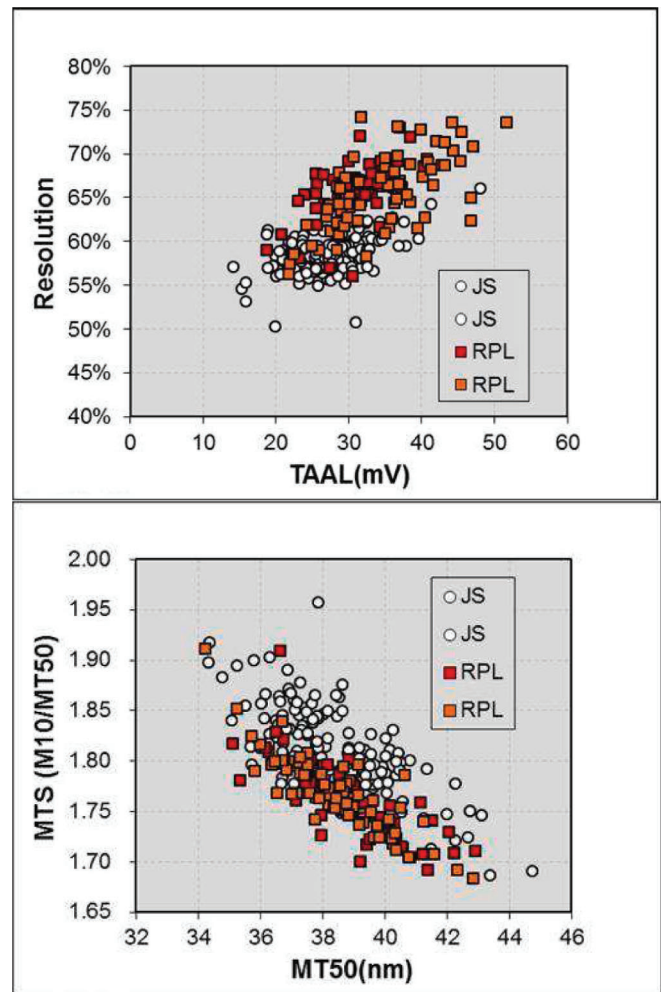


Fig. 9. Experimental results of (a) Resolution and (b) MTS from spin-stand dynamic performance measurement (S-S spacing RPL: 23 nm, JS = 28 nm).

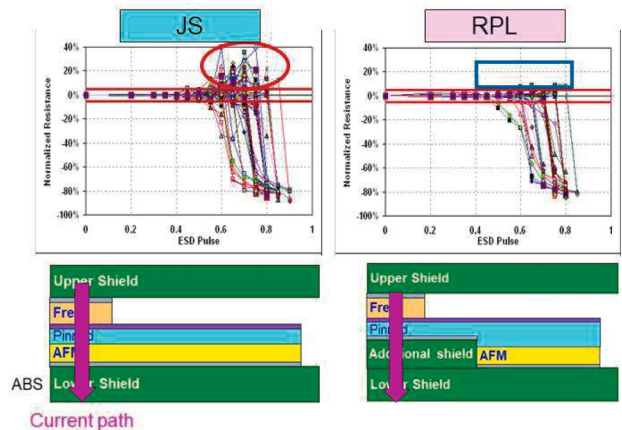


Fig. 10. Experimental results of ESD robustness.

adjacent tracks. The authors proposed an “array of closely spaced readers” to overcome cross track inter-symbol interference (ISI) or by processing the two dimensional readback samples in software after multiple pass readback. In today’s storage, multiple passes are reserved for error recovery and sustained data rates require readback at a single pass. Elidrrissi et al. [26] show 17.5 % areal density gain by using a true

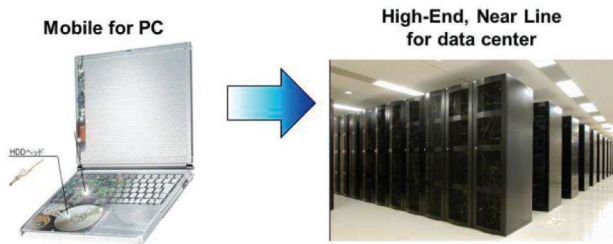


Fig. 11. Usage transition of HDDs.

two dimensional magnetic recording (TDMR) equalizer with 2 or 3 readers compared to a single reader. By using captured waveforms measured at various cross track locations, Matthew et al. [27] projected up to 30 % enhancement in capacity by using two or three read elements placed at different cross track positions.

In order to realize the multi reader schemes envisioned by TDMR Recording technologies, several changes to reader architecture have been proposed such as those presented by Garfunkel et al. [28]. Two dimensional readers are typically fabricated as two readers sequentially formed on a wafer separated by a typical distance in the range 50–100 nm. Any cross track spacing can also be realized by physically offsetting the two readers on the wafer. Such readers are usually aligned at MD skew of the disk drive in order to derive the maximum benefit of two reader averaging. Most commercial applications of two or more readers have been using a hardware analogue of multi-pass reading of the same data as opposed to true ISI reducing TDMR recording schemes. As presented in the patent [29], connectivity to two leads per read head in addition to reduced downtrack spacing requirements impose serious restrictions. Garfunkel et al. [29] also teach methods to provide longitudinal biasing to dual read heads placed downtrack on the wafer. Exchange coupling provided by the top shield of each sensor can provide coupling to soft ferromagnetic layers on the sides of each free layer extending the JS concept to TDMR heads (Figs. 12 and 13).

5. Spin transfer torque noise

Another challenge that the read sensor designs face is the noise induced by the spin transfer torque (STT) when RA is reduced to below $0.7 \Omega \cdot \mu\text{m}^2$. STT was first calculated for metallic spin valves in 1996 [30,31], and was then extended to magnetic tunnel junctions in 2005 [32]. During the past two decades, it has been widely demonstrated in labs and in multiple industries including magnetic nonvolatile memory [33] and magnetic assisted recording [34].

The electron flow in the read sensor is spin-polarized by AP1 due to spin dependent scattering so that the majority of the electrons have their spin polarization in the same direction as the magnetic moment of the AP1. After they tunnel through the oxide barrier, the spin angular mo-

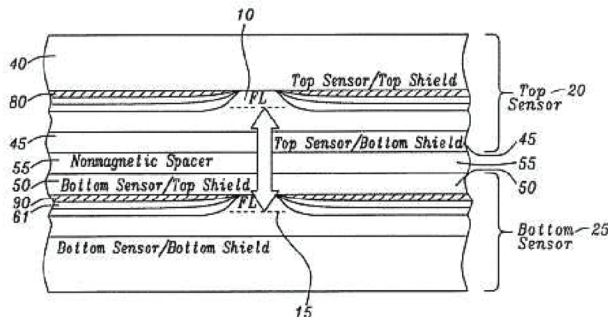


Fig. 12. Schematic showing the layering and biasing of the dual reader sensors for TDMR. (from US Patent 9601138 B1).

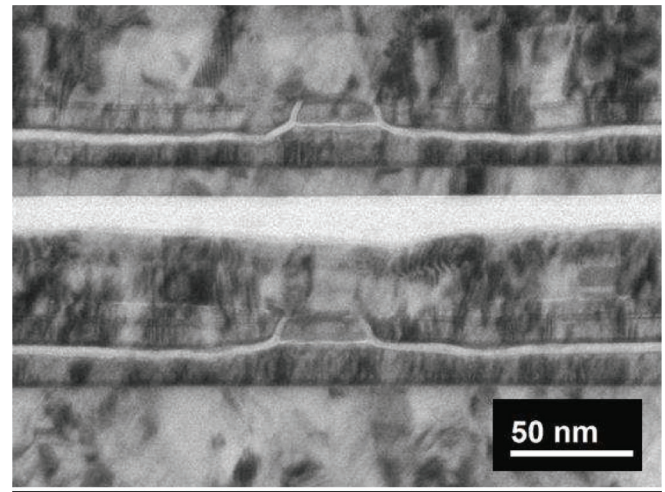


Fig. 13. ABS TEM image of a dual element reader used in TDMR.

mentum of the polarized electrons interacts with the local magnetic moment of FL via the STT. The STT, whose magnitude is proportional to the biasing voltage across the tunnel barrier, is composed of two terms: one is the damping-like torque, in the direction of $\hat{m}_{\text{FL}} \times (\hat{m}_{\text{FL}} \times \hat{m}_{\text{AP1}})$, where $\hat{m}_{\text{FL}}$ and $\hat{m}_{\text{AP1}}$ are the unit vectors in the direction of FL and AP1 magnetization respectively, and the other is the field like torque, in the direction of $\hat{m}_{\text{FL}} \times \hat{m}_{\text{AP1}}$ [32]. The field like torque is equivalent to an additional bias-dependent exchange interaction between the FL and the AP1, causing a shift to the asymmetry of the read sensor transfer curve. The damping-like STT term is collinear with the Gilbert damping torque of the FL. When the electrons flow from the AP1 to the FL, if the angle between $\hat{m}_{\text{FL}}$ and $\hat{m}_{\text{AP1}}$ is smaller than 90° , the damping-like STT is in the same direction as the Gilbert damping torque, so that the FL oscillations out of equilibrium are quickly damped out. If the angle between $\hat{m}_{\text{FL}}$ and $\hat{m}_{\text{AP1}}$ is larger than 90° , the damping-like STT competes with the Gilbert damping torque, so that the FL oscillations become more difficult to decay with time. Above a certain voltage threshold, stable oscillations in the FL magnetization start to be developed, yielding a measurable noise in the TMR signal of the read sensor. Under this biasing direction, STT induced noise is observed when FL is more antiparallel to AP1, i.e. above a magnetic bit from the medium that is into the air bearing surface (ABS) when AP1 points out of the ABS. Similarly, when electrons flow from FL to AP1, STT induced noise is observed when FL is more parallel to AP1, i.e. above a magnetic bit from the medium that is out of the ABS along the same direction as AP1 (see Fig. 14).

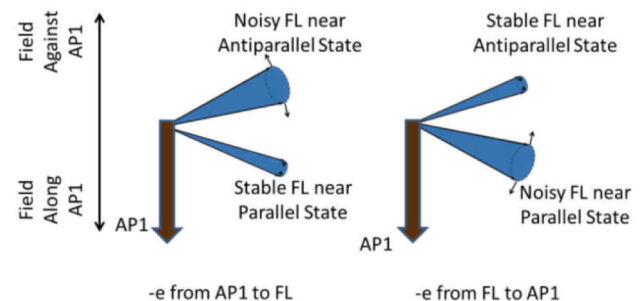


Fig. 14. Schematic of AP1 and FL magnetization with an applied field or magnetic medium field that is collinear with the AP1 magnetization. When electrons flow from AP1 to FL, STT induced noise is found with FL and AP1 magnetization near an antiparallel stte; when electrons flow from FL to AP1, STT induced noise is found with FL and AP1 magnetization near a parallel state.

The STT induced noise becomes a concern as it degrades signal-to-noise ratio of the read sensor when we further reduce the RA of the tunnel barrier in order to meet the requirement of smaller sensor sizes. Generally speaking, if the STT induced noise is clearly observed, the biasing polarity where the electrons flow from the FL to the AP1 will be a better choice. In current read sensors, all devices target the same applied voltage under a zero external field, and are driven by a current source. Therefore, the antiparallel state between FL and AP1 due to a field against AP1 moment direction has a higher applied voltage across the tunnel barrier compared to that under a zero external field, while a parallel state has a lower applied voltage. As the damping-like STT's magnitude is proportional to the biasing voltage on the same device [32], the STT induced noise is stronger under the antiparallel state with electrons flowing from AP1 to FL, as compared to that under the parallel state with electrons flowing in the opposite direction. However, this statement is also not always true, as with a reduced RA, exchange interactions between the AP1 and the FL via the tunnel barrier also become stronger. In this case, read sensors tend more to be closer to a parallel state, even with a field against the AP1 direction, so that the STT noises of the sensor closer to the antiparallel state, with electrons flowing from AP1 to FL, can sometimes be avoided.

Fig. 15 shows the measured reader sensor noise as a function of an applied magnetic field in a transverse direction, into or out-of ABS, where positive field is defined as the direction against the AP1 magnetization. With the applied current where the electrons flow from the FL to the AP1, STT induced read sensor noise is mostly observed with a negative applied field, i.e. parallel state between the FL and the AP1 magnetization; and the applied current in the opposite direction results in a stronger STT noise under the antiparallel state between the FL and the AP1 magnetization, consistent with the discussions above.

Approaches to reduce any sources of sensor noise are always favored by read sensor designers. There is not much one can do to tune the tunneling efficiency between AP1 and FL, as it is also a deterministic factor for the TMR signal. One direct way to reduce such noise is to increase the damping of the FL that competes against the STT. Though heavy metal impurities can effectively increase the damping constant [35], they may also impact the MR ratio affecting the signal amplitude and increase the thermally induced magnetization noise of the read sensor [36]. Another way is to introduce additional STT on the opposite side to cancel to the STT induced noise from the AP1 [37]; but this may also increase the shield to shield spacing.

6. Limitations for advanced densities

For both TMR and GMR, thermal magnetic noise becomes a major concern with decreasing sensor volume, Ω . To combat the increasing noise power $\propto 1/M_s\Omega$ [38,39], the saturation magnetization M_s of the sensor has to be raised proportionally as $1/\Omega$. This will eventually pose a hard limit on the minimum sensor size when the highest possible M_s is reached.

A simple estimate of the SNR using present-day numbers is as follows. The thermal magnetic noise voltage is given by $\sqrt{\frac{4k_B T \mu_0 \alpha_G W}{\gamma M_s \Omega}} \frac{dV}{dB}$ [39], where $T \approx 300\text{K}$ is the sensor temperature, $\alpha_G \approx 0.01$ is the Gilbert damping constant, γ is the electron gyromagnetic ratio, $\frac{dV}{dB} \approx 0.2 \frac{\text{V}}{\text{T}}$ is the sensor sensitivity, Ω is the sensor volume and $W \approx 1\text{GHz}$ is the bandwidth. For a sensor with track width (TW) = 20 nm, sensor height (SH) = 20 nm, thickness (t) = 10 nm (where thickness direction is perpendicular to the TMR barrier) and $M_s = 8 \times 10^5 \frac{\text{A}}{\text{m}}$, the thermal magnetic noise voltage 0.11 mV is comparable to the shot noise voltage 0.24 mV (at $RA = 0.5\Omega\mu\text{m}^2$). Further assuming $MR = 0.7$, $V_{bias} = 140\text{mV}$, and $u = 40\%$, the signal voltage is 20 mV which yields a SNR of 45 dB. Mandating the same SNR, reductions to current sensor dimensions is limited to $\sim 30\%$ due to the availability of material M_s .

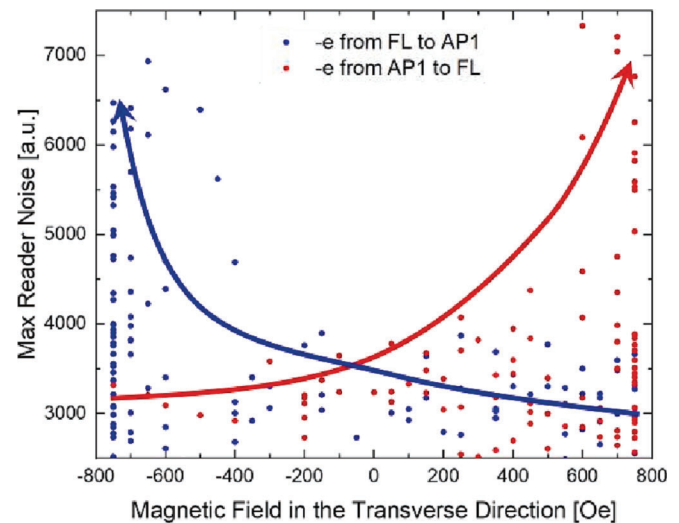


Fig. 15. Measured reader sensor noise as a function of transverse magnetic field into or out-of ABS, where positive field is defined against the AP1 magnetization.

7. Conclusion

Transition from GMR to TMR has extended HDD readback performance by over 15 years providing almost two orders of magnitude enhancement in achievable recording densities. This was all made possible by increases in MR ratio, reductions in RA, dimensional and geometric advancements and the ability to keep magnetic and shot noise in check as well as addressing spin torque induced noise. From simple scaling, it is expected that TMR will enable several additional generations of HDD products to come.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Moris M Dovek has Patents referenced in this paper and other related patents pending to Headway Technologies, TDK Corp, SAE Magnetics. Moris M Dovek has Patents referenced in this paper and other related patents issued to Headway Technologies, TDK Corp, SAE Magnetics.

Data availability

This is a review article. All used data has been previously published.

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