INVITED PAPER

Spintronics, Magnetoresistive Heads, and the Emergence of the Digital World

Two breeds of spintronics sensors based on giant magnetoresistance and tunnel magnetoresistance are part of the technology development that enabled the increase of storage density of hard disk drives by several orders of magnitude, laying the foundation of today's information age in the form of data centers installed by the cloud computing industry.

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ABSTRACT | The development of spintronics has had a dramatic impact on the evolution of the magnetic hard disk drive and, in turn, on the ubiquitous nature of digital data in modern society. The advent of the magnetoresistive read head technology transitioning from the anisotropic magnetoresistance read head to the spintronics-based giant-magnetoresistance read head and the tunneling magnetoresistance read head were major drivers in this remarkable increase in digital storage. We will review the development of magnetoresistive read head technologies and their impact on digital data storage. We will then highlight the current state-of-the-art sensor and potential future technologies.

KEYWORDS | Giant magnetoresistance; magnetic recording; magnetoresistance; magnetoresistive devices; spintronics; tunneling magnetoresistance

I. THE EMERGENCE OF HIGH-DENSITY HARD DRIVES AND DIGITAL DATA

Magnetic storage has played a key role in audio, video, and computer development since its invention more than 115 years ago by Poulsen [1] and continues to play a dominant role in data storage today. The first hard disk drive, the IBM 350 magnetic disk file system, was introduced by IBM in 1956 as part of the Random Access Method of Accounting and Control (RAMAC) 350 computer systems [2]. The first IBM 350 had a total storage capacity of 4.4 MB. The data were stored on a stack of fifty 24-in-diameter disks that spun at 2000 r/min. The storage areal density was 2 kb/in^2, the data rate was 70 kb/s, and the estimated cost for storing these digital data was on the order of \$10 000/MB (\$10 M/GB) in 1956. For comparison modern high-capacity hard drives can now store 10 TB of data (2×10^6 more data than the original IBM 350) on seven 3.5-in disks with storage densities approaching 1 Tb/in^2, data rates exceeding 1 Gb/s and most importantly can now be sold for less than \$0.01 per gigabyte of data stored. Thus, one sees a nearly 10^9 increase in storages densities over the 60-year development history [Fig. 1(a)] of the hard drive with a corresponding $\sim 10^9$ decrease in the cost per bit [Fig. 1(b)].

It is this dramatic increase in storage densities with the corresponding decrease in cost with time that has helped drive the modern digital data world. If one looks at total data storage capacity in the world versus year you see two dramatic trends [3]. The first is that the supply of total storage for data has grown and continues to grow exponentially. From 1986 to 2007, the total storage capacity grew at a compound growth rate (CGR) of 23% per year and this growth is accelerating. The second, and a bit more surprising, is that storage of digital data is a relatively recent phenomenon. In 1993, only $\sim$1% of data storage capacity was digital and most data were stored in analog form (mostly on video and other flexible tape) [3]. This, in retrospect, should not be surprising considering that in the early 1990s 1 GB of digital storage using a hard drive would cost about \$2000

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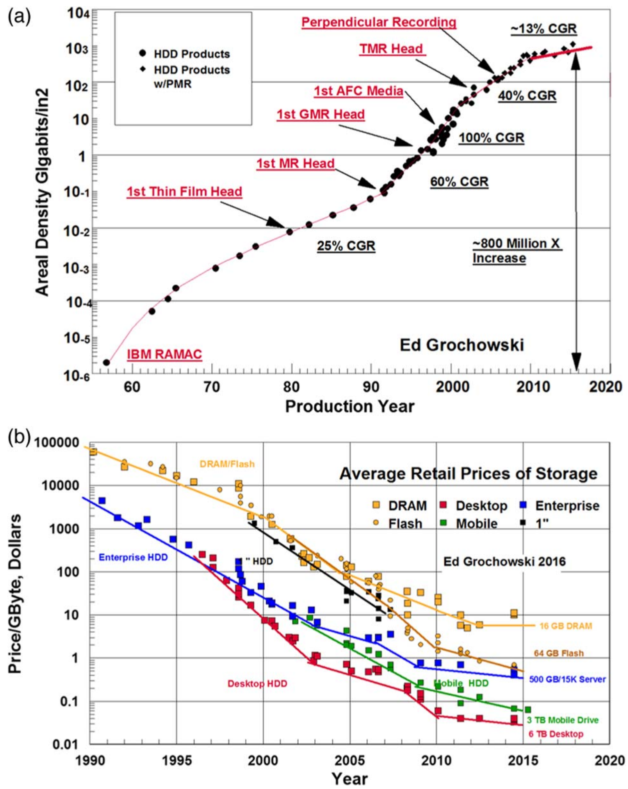

Fig. 1. ***(a) Areal density of magnetic recording for hard disk drives versus year with the corresponding compound growth rate (CGR) of the areal density. Included in the graph are the years for the introduction of new record head and media technologies. (b) Average retail price digital data storage per gigabyte of storage versus year for various magnetic hard disk drive platforms (desktop, enterprise, mobile and the 1″ Microdrive) was well as charge-based DRAM and Flash storage. Images supplied by E. Grochowski.***

[Fig. 1(b)]. Even as late as the year 2000 only 25% of data was stored digitally. The year 2002 could be considered the beginning of the digital age because it was the first year digital storage capacity exceeded total analog capacity worldwide. By 2007, the percentage of data stored digitally had jumped to 94% and almost all data are now stored digitally with a majority of these data stored on magnetic hard disk drives [3].

Digital computation has become so indispensable that it is now simply unimaginable to think of our society functioning without it. Future economic development and security will depend on the ability to store, transmit, manipulate, and mine ever-increasing amounts of digital data (the digital economy). Estimates of the total amount of digital data generated or copied in 2013 alone was about 44 trillion GB (4400 exabytes or 4.4 zetabytes) [4]. This is expected to grow at a rate of 40% per year into the next decade. This growth is driven not only by increasing online activity but also by new smart devices that monitor and manage the world while connected to the Internet, the Internet of Things (IoT) [4], [5]. To meet the demands to store this remarkable amount of data, the hard drive industry ships greater than 500 exabytes of storage capacity each year and this is expected to increase to close to 2000 exabytes (2 zetabytes) per year by the end of the decade driven in large part by the growing needs for massive storage libraries in the cloud [6].

This dramatic shift to storing data from mostly analog to the current digital world started in the 2000s and was driven, in large part, by the emergence of magnetoelectronics and spintronics exemplified by the introduction of the anisotropic magnetoresistive (AMR) read head in 1991 [7], the giant magnetoresistive (GMR) read head in 1997 [8]–[11], and the tunneling magnetoresistive (TMR) head in 2006 [11]. Prior to the introduction of the magnetoresistive read head, the storage densities of hard drives had increased at a CGR of 25% or a doubling of storage densities about every six years [shown in Fig. 1(a)]. With the introductions of the AMR head in 1991 the CGR increased to 60% per year or doubling every 18 months which is the historical trend of Moore's Law for the density of transistors on a chip [12]. With the introduction of the GMR head, the storage density CGR was able to increase further to nearly 100% per year (doubling every year) for the next five years. More recently, the areal density growth has slowed resulting primarily from thermal instabilities limiting the magnetic storage density, known as the superparamagnetic effect [13], [14], as well as other technical challenges for high density storage [15]. However, to put these numbers in context, had the HDD industry continued to grow at the historic 25% CGR after 1991, the current storage densities would be two orders of magnitude lower than current densities.

For the decade from 1992 to 2002, the data storage densities increased by roughly 400 times with a nearly 1000 times decrease in the cost per bit [from ∼\$2000/GB to ∼2\$/GB, as seen in Fig. 1(b)]. For comparison, the cost of storing data on paper or film was on the order of \$100/GB. Also seen in Fig. 1(b) there was also a significant decrease in the cost of DRAM and Flash memory, particularly starting in 2000. Thus, it is easy to see why there was a dramatic transition to digital data storage starting in the late 1990s as digital storage became significantly less expensive than traditional approaches and the emergence of digital cameras, digital video recorders, and other consumer products where storing digital data on hard drives was the most cost-effective approach. This dramatic transition is reflected in the press release for the 2007 Nobel Prize in Physics [16] that was awarded to Albert Fert [17] and Peter Grünberg [18] for the discovery of GMR and starts with "This year's physics prize is awarded for the technology that is used to read data on hard disks. It is thanks to this technology that it has been possible to miniaturize hard disks so radically in recent years. Sensitive read-out heads are needed to be able to read data from the compact hard disks used in laptops and some music players, for instance." The press release concludes with "GMR can

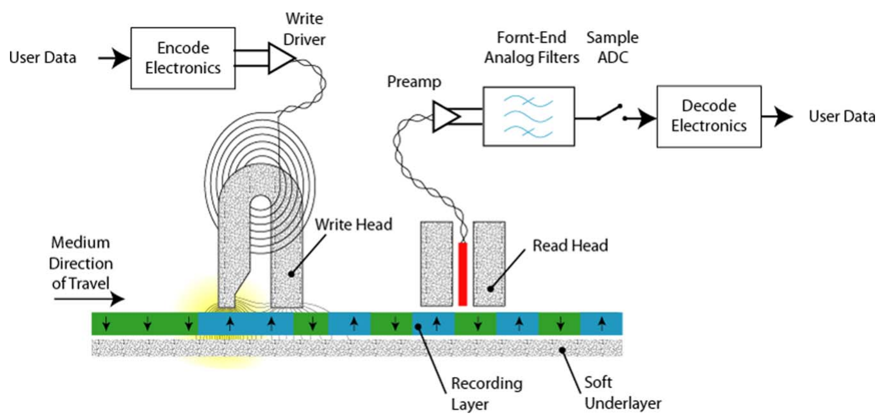

Fig. 2. ***Schematic of modern perpendicular magnetic recording systems with separate write and read heads. A bit pattern is shown in the recording layer. The soft underlayer can be viewed as an extension of the write head and guides the write field.***

also be considered one of the first real applications of the promising field of nanotechnology."

II. AMR AND GMR READ HEADS

If one compares the basic principle of magnetic recording from the IBM 350 in 1956 to a modern hard drive they are remarkably similar in their basic operation. The main difference is the size of the critical dimensions which were on the order of tens to hundreds of micrometers in the 1950s and have decreased to tens of nanometers or less today. The only qualitative difference was the introduction of the separate read and write components (heads) in 1991. Previous to 1991 (dating all the way back to Poulsen in 1889) the writing and reading of data were done by the same head which was a small electromagnet consisting of a coil of conducting wire and a ferromagnetic split (open) core. To write data, a time-varying electrical current is sent through the coils so that the electromagnet generates a time-varying magnetic field at the open core gap that writes a spatially varying magnetic data pattern onto the magnetic disk as it passes under the gap region of the head. To read back the data, the same head is then passed over the recorded data pattern. The magnetization of the electromagnet core of the head would respond to the magnetic fields generated by the recorded data pattern and this changing magnetization in the head generates an inductive voltage at the electromagnet coil that was read out as signal. This operation was already described in the 1899 patent by Poulsen [1] as "a paramagnetic body, such as a steel wire or ribbon, which is moved past an electromagnet connected with an electric or magnetic transmitter, such as a telephone, is magnetically excited along its length in exact correspondence with the signals, messages, or speech, delivered to the transmitter, and, further, that when the magnetically-excited wire is again moved past the electromagnet it will reproduce the said signals, messages, or speech." This basic approach was used in various forms until 1991.

However, as the size of the recorded bits was decreased by reducing the write head dimensions, the shrinking size of the head meant that read-back signals also decreased excessively. The introduction of the magnetoresistive (MR) read head, using a ferromagnetic film instead of an electromagnet as the reading component, separated the writing and reading process and allowed the read and write heads to be separately optimized. The MR thin-film head has increased sensitivity, enabling improvements in other components, and it reads the field amplitude directly via a corresponding change of resistance in the sensor film, as opposed to the inductive process of a traditional coil-based head. Thus, the readback of a MR sensor is independent of the velocity of the media relative to the disk. A schematic of the hard drive recording and readback process in shown in Fig. 2 where the recording head is composed of a separate read and write element, flies in close proximity (< 10 nm) to a granular recording medium [19], [20]. The inductive write element records the time-varying current into magnetization patterns. The information is then read back with the read element by measuring the stray magnetic fields above the surface of the disk that arise from the varying magnetic pattern. There is often a misconception that the data are read back as "ones" and "zeros." In fact, the read head sensor element responds continuously to the magnetic field pattern above the disk and then a signal processing unit transforms this analog readback signal into a stream of digital data bits. Thus, magnetoresistive heads (MR heads, GMR heads, or the current TMR heads) are actually analog devices that detect the sign and magnitude of the magnetic fields above the disk with high resolution, rather than directly detecting the binary magnetization of the stored bit.

The basic operation of the magnetoresistance head is to convert the magnetic field that exists above the data

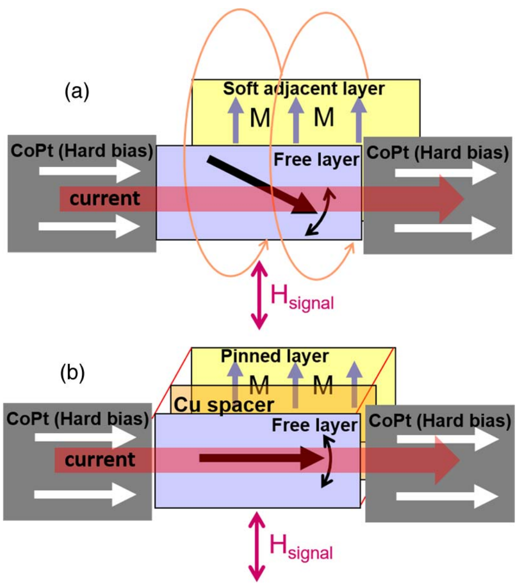

Fig. 3. ***Schematic of components of a simple (a) AMR and (b) GMR read head. In both cases, the blue free magnetic layer is the sense layer responding to an external magnetic field. The yellow magnetic layer is the soft adjacent layer in (a) and the reference layer in (b).***

bits recorded on the disk to a change in resistance that can be read out. The initial concepts used the bulk magnetoresistance properties of ferromagnetic materials known as anisotropic magnetoresistance (AMR) which arises from the spin-orbit interaction and the resistance depends on the orientation of the magnetization of the current relative to the magnetization direction [21]. Usually the resistance is higher for the current parallel to the magnetization and lower for the current perpendicular to the current. The initial magnetoresistive head was based on AMR in a single permalloy ($Ni_{80}Fe_{20}$) layer, which provides a change in resistance of about 2%–4% as the magnetization in the layer rotates from parallel to perpendicular to the direction of current flow. A schematic of the AMR head is shown in Fig. 3(a). The resistance varies as $\cos^2\theta$ where θ is the angle between the current direction and magnetization. Therefore, the signal extrema are achieved at angles of 0° and 90°, and the steepest response slope is at an angle of 45°. Thus, to achieve the highest sensitivity to small changes in the orientation of the magnetic sensing layer to an external field, the read head was designed so that in the absence of a magnetic field the magnetization of the permalloy sense layer was at 45° to the current direction. In this way, when the magnetic layer rotates to align with positive or negative fields above the recorded bits, the resistivity will either increase or decrease with maximum relative amplitude.

To achieve this overall magnetic orientation, the Oersted magnetic fields generated by the current in the sense layer caused an adjacent soft magnetic layer to align its magnetization perpendicular to the current direction. In a properly designed head, the magnetic stray fields generated by this adjacent layer, in combination with an additional external horizontal field provided by hard-magnetic bias layers deposited on either side of the sensor, caused the magnetization of the sense layer to rotate to 45°. Another key role of the combined fields of the hard bias layers and the soft adjacent layer was to suppress the formation of domains in the free layer. Early AMR sensors suffered from Barkhausen noise originating from the buckling domain structures that formed in the MR elements and the subsequent irreversible domain-wall-state transitions during the read process [22]. The biasing fields stabilized a single-domain state of the sensor dramatically reducing magnetic noise by confining the response of the sensor layer to rotation of the magnetization. Successfully achieving this design and introducing it reliably into the hard-drive market was a remarkable engineering feat [22] and set the stage for future sensor advancements in the future. In this simple initial design, the resistance change was not completely linear to applied field ($\cos^2\theta$ is not linear to small changes in θ about 45°) although more sophisticated designs could make the response essentially linear [23].

The AMR head was a dramatic and important contributor to the evolution of the hard drive and was introduced in 1991 in the 3.5-in IBM 0663-E12 1-GB drive which provided the highest areal density available at the time. The increased sensitivity of the AMR head significantly improved the readback signal and allowed the media to be thinned, yielding higher resolution data. However, the main limitation to the continued use of the AMR heads is the fact that AMR is a bulk effect. To achieve higher recording density requires reducing the dimensions of the read sensor (to sense the smaller bits with high resolution) including the physical thickness of the magnetic sense layer. As the magnetic sense layer is thinned down and approaches the mean free path of the conduction electrons (~10 nm), scattering from the surfaces begins to dominate and the sensitivity decreases dramatically. It is because of this limitation that the discovery of GMR in 1988 was particularly fortuitous [17], [18], [24], [25]. The basic phenomenon of GMR results with current flowing through two magnetic elements separated by a thin nonmagnetic spacer layer. The current becomes spin polarized by transmission through or upon reflection from the first magnetic layer and mostly maintains this polarization as it passes through the nonmagnetic spacer and enters and interacts with the second ferromagnetic layer. This interaction leads to a change of resistance depending on the relative orientation of the neighboring magnetic layers. Unlike AMR, GMR is primarily interfacial scattering and requires the exchange of electrons between layers. This leads to the GMR effect increasing, at least initially, as the magnetic layers are thinned and the GMR heads sensitivity improved as the density increased.

Fig. 3(b) shows a simple schematic of a GMR head where two magnetic layers are separated by a thin conductive layer allowing the layers to share electrons between them. At least schematically the GMR and AMR heads appear quite similar. However, for the GMR head, the resistance is highest when the layers are parallel and lowest when they are antiparallel and the resistance depends roughly on $\cos\theta$ where θ is now the angle between the two magnetic layers. The sensor is designed to have the one layer pinned (the reference layer) that does not respond to a magnetic field. In Fig. 3, this is achieved by exchange biasing the magnetic layer to an antiferromagnetic layer [26], [27]. The second magnetic layer is free to rotate with the application of an external magnetic field. In the absence of an applied field the 90° orientation of the free and reference layers provides the highest sensitivity and makes the resistance roughly linear for small fields (i.e., small angular deviations from 90°). This general structure is known as a "spin valve," as it refers to the structure where, under a constant applied voltage, the relative orientation of the magnetization in two adjacent layers controls the flow of current through the device [28]. A key aspect of the spin-valve device was the ability to hold the reference layer fixed, while decoupling the free layer from the fixed layer. This allows the free layer to rotate in relatively small applied fields, in contrast to the initial discovery of GMR in antiferromagnetically exchange-coupled magnetic multilayers where the saturation fields were relatively high [24].

An example of a more advanced GMR read head as described in detail in [11], [29], and [30] is shown in Fig. 4. In this design, the reference layer is combined with a pinned layer in an antiparallel-coupled CoFe/Ru/CoFe multilayer stack exchange biased on one side by an antiferromagnetic layer. The antiparallel coupling is mediated by a ~0.7-nm Ru layer. The two Co layers are nearly the same thickness, resulting in a low net moment for the overall reference layer, and thereby limiting stray magnetic fields that could interact negatively with the free layer (in contrast with the AMR head where the stray fields were an asset). The CoFe/Ru/CoFe net magnetization direction is maintained by coupling to an antiferromagnetic layer (e.g., IrMn or PtMn) [26], [27], [29]. For a spin-valve read head, the orientation of the reference layer is into/out of the plane of the picture as shown in Fig. 4. The free layer is a CoFe/NiFe composite where the CoFe layer enhances the GMR, while the magnetically soft NiFe layer enhances field sensitivity. The equilibrium alignment of the free layer is perpendicular to the reference layer and is stabilized by the dipolar field provided by the hard bias layers. For these GMR sensors, the current leads, together with the hard bias layers, are connected to the edge of the sensors and the current flows within the plane of the film known as the current-in-plane geometry (CIP). The sensor is then placed, isolated by insulating gap layers such as Al_2O_3, between two soft magnetic shields to reduce any stray magnetic fields and screen the sensor from recorded bits other than those directly below the read head.

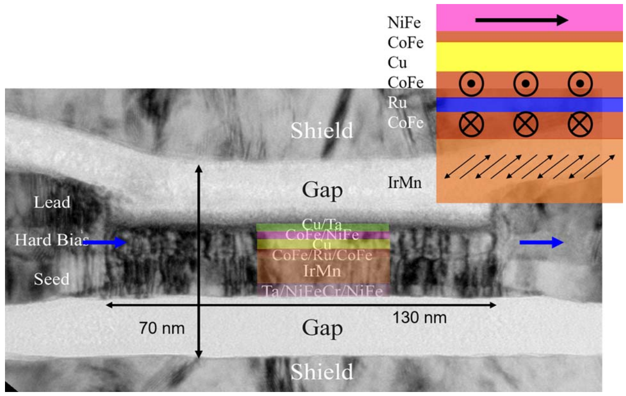

Fig. 4. ***Transmission electron microscopy cross section of a CIP GMR read-head sensor from [29]. False color has been added to a small portion of the sensor to help distinguish the various metallic layers from one another. The down-track shield-to-shield spacing is 70 nm. The full trackwidth (total width of the sensor) is 130 nm. Schematic of the orientation of the magnetic layers is shown in the upper right. The magnetization of the antiferromagnetically coupled reference layers is oriented into and out of plane and biased by an IrMn layer. The CoFe/NiFe composite free layer is aligned with the magnetic field generated by the hard bias layers indicated by the blue arrows.***

The GMR spin-valve sensor was a remarkable innovation and can be viewed as the birth of modern spintronics [31]. Not only did it lead to dramatic increases in hard-drive storage densities but also GMR sensors (along with TMR sensors) are widely used as field sensors in a broad range of applications such as linear and rotational position sensors, current and current limit detection, and vehicle sensors where they work by detecting small changes in the magnetic field [32]. They have also been used in numerous biological applications [33]. GMR sensors are well suited for biomagnetic applications due to their small size, low cost, high field sensitivity, and compatibility with portable applications. Examples include detecting magnetic fields generated by action potentials propagating along the axon of a neuron [34], magneto-cardiography and magneto-encephalography [35] as well as detection of biomarkers tagged by magnetic nanoparticles [36]–[38].

III. TMR READ HEADS AND BEYOND

In 2006, the industry transitioned to the currently-used TMR recording head, in part because of the demonstration of increased magnetoresistive effect (increased signal-to-noise ratio) using the electronic tunneling process compared to standard GMR, but principally due to

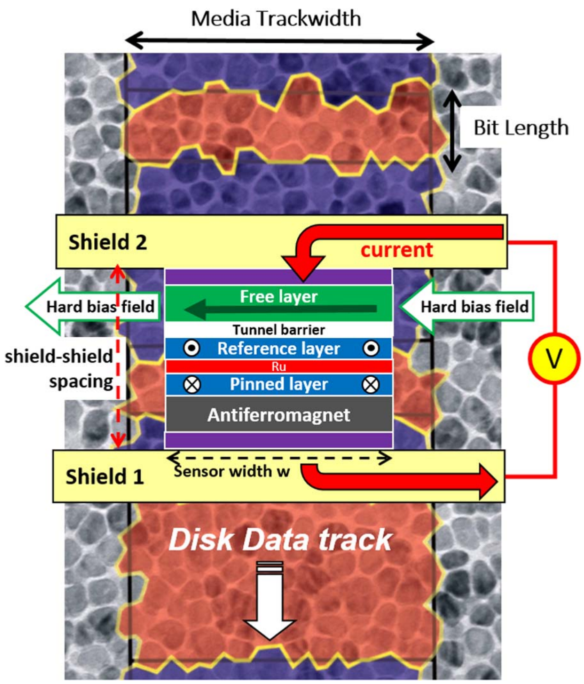

Fig. 5. *Schematic of a CPP–TMR head over a data track. The data are encoded as regions of magnetization either into (purple) or out of (red) the plane. The magnetic layer is oriented in the same fashion as Fig. 3 but with the current flow perpendicular to the layers and tunneling across the thin MgO layer (white). The hard bias layers are not shown.*

limitations to continued scaling of the GMR head to ever-smaller dimensions. In the CIP geometry, as the sensor size decreased, the effective GMR ratio decreased with decreasing sensor width due to the extra parasitic resistance from the damaged regions where the current leads and hard bias layers are attached to the side of the sensor during microfabrication (referred to as the contiguous junction process) [39]. Additionally, for higher resolution, it is necessary for the two shields above and below the sensor to be brought closer together, and this became increasingly difficult to do without accidently shorting the sensor due to the ultrathin insulating gap layers required. Both of these issues are successfully resolved in the TMR sensor where the magnetic shields are in electrical contact with the sensor and also serve as the top and bottom electrical contacts [11], [30]. The sensor is electrically isolated on its sides from the magnetic hard bias layers (not shown in Fig. 5) such that the current flows normal to the sensor layers, a geometry known as current perpendicular to the plane (CPP). In TMR, the magnetic sensitivity arises from the tunneling conductance across the thin insulating layer, first demonstrated in practical structures above room temperature in 1995 [40], [41]. While these original results used amorphous Al_2O_3 tunnel barriers, the current heads use crystalline MgO tunnel barriers. MgO barriers have an advantage over amorphous barriers in that there is an additional spin selectivity in the tunneling process due to the band structure of MgO, so the size of the magnetoresistance is much larger than one expects from the spin polarization of magnetic electrode alone [42]–[44]. The change of resistance can be greater than 100% with MgO barriers, with comparatively high electrical conductivity resulting in lower resistance and thus lower noise.

Shown in Fig. 5 is a schematic of a TMR read head over a bit pattern highlighted on the recording media. The recording media are made up of crystalline magnetic grains with an engineered weak intergrain exchange coupling, resulting in transitions from one bit to the next which roughly follow the grain boundaries. The granular microstructure allows writing and storing transitions with relatively high spatial precision. However, the ultimate density is limited by the grain size. Due to the granular structure of the recording medium, small deviations from the intended transition positions occur, known as transition jitter. For a storage density of 500 Gb/in^2 the grain size is $\sim$7 nm for typical media with a bit size of 15 nm in the down-track direction and 60 nm in the cross-track direction. To correctly read the data back, the transition jitter must be about 10% of the bit length or only about $\sim$1.5 nm. Thus, the accuracy achieved in placing these transitions is quite remarkable for a mechanical device such as an HDD. The recording head dimensions must match the scale of the recorded bit. For the corresponding recording head the sensor width is $\sim$35 nm, the shield-to-shield spacing is $\sim$35 nm, and the sensor height (out of the plane of the figure) is $\sim$35 nm. The sensor width needs to be less than the recorded track width to avoid track-edge noise. The MgO barrier is only 0.8 nm thick with a resistance-area (RA) product $\sim 1\ \Omega - \mu\mathrm{m}^2$.

As mentioned earlier, the continued growth of the storage densities of hard drives has slowed in recent years due, in large part, to thermal stability limitations of the media. That is, it is increasingly difficult to scale the media grains to smaller size and maintain the thermal stability of the media while still being able to write the media with a traditional recording write head. There are several disruptive technologies that are under development to overcome these limitations, including bit patterned magnetic recording (BPMR) [45] where the media are patterned into single-domain islands and heat-assisted magnetic recording (HAMR) [46]–[48] where an optical transducer heats the media near the Curie temperature to write the data, or a combination of the two [48]. While these technologies address the writing and storage of the data, the read head will also have to scale to smaller dimensions to read back the resulting data for any such successful approach.

There has been remarkable progress in the TMR head but there are increasing challenges with scaling TMR heads to even smaller dimensions, as was experienced previously with the AMR and GMR heads. The main challenge is that the reduced physical dimensions continue to reduce the required RA product necessary to maintain a reasonable device impedance. The maximum impedance value ($< \sim 1$ k Ω) is constrained by performance requirements of the systems, including data rate and noise requirements [11]. Reduction of the RA product for a given tunneling material is achieved primarily by thinning the barrier which has appeared to have reached a limit near 0.8 nm. If TMR cannot continue to scale down to ultralow RA values $\ll 0.5\ \Omega - \mu\text{m}^2$, there is advantages to transitioning back to a fully metallic CPP–GMR sensor to achieve a reasonable impedances at the smallest dimensions [49]. CPP–GMR sensors are challenging due to their low resistance, low magnetoresistance values, as well as current-induced noise and magnetic instability from spin-torque effects [30]. However, significant progress has been achieved in the development of high-spin-polarized magnetic electrodes with high magnetoresistance, with extensive focus on ferromagnetic Heusler alloys [50]–[53] which can be 100% spin polarized.

Thus, the magnetoresistive sensor and spintronic spin valves in particular have continuously evolved to meet the geometrical requirements of shrinking data bits. However, spin-valve and tunnel-valve sensors are now complex multilayer structures with many specialized substructures necessary to achieve the required magnetic stability and performance. Eventually, at ultrahigh densities, the shield-to-shield spacing needs to continue to decrease and it becomes increasingly difficult to have all the layers that make up the spin-valve structure fit between the shields. To address this new geometrical frontier there is potential to use nonlocal spin devices. The long spin diffusion lengths found in metallic systems allow nonlocal spin diffusion in which the spin and electrical degrees of freedom are decoupled [54], [55]. In nonlocal devices, spin-polarized currents are injected from one ferromagnetic electrode into a nonmagnetic material, and the resulting spin accumulation diffuses away the injection point and can be detected as a voltage at a second ferromagnetic electrode [54]–[59]. A schematic head design from [57] is shown in Fig. 6 where the reference and free layers are spatially separated, allowing a much narrower read gap < 20 nm. Nonlocal spin valves have recently been demonstrated using high spin-polarized Heusler alloy electrodes that give large signals with low contact resistance needed for high data rate hard-drive applications [57], [58].

Another novel spintronic approach to achieve high sensitivity for ultrasmall field sensor is to use a nano-spin-torque oscillator (NSTO) [60]–[63]. The basic phenomenon of spin torque is related to GMR and TMR. Commensurate with the magnetoresistance, there is a transfer of angular momentum from the polarized current to the free layer that provides an effective torque [64]. This spin torque can oppose the intrinsic damping of the magnetic layer resulting in, for the proper

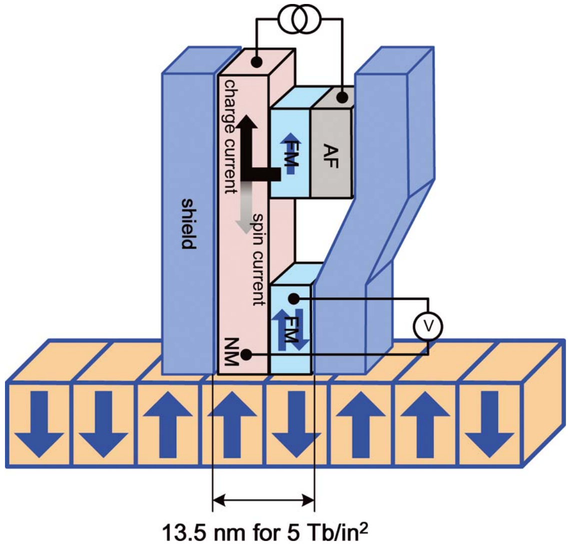

Fig. 6. ***Schematic image of read sensor using a lateral spin-valve device. Since the spin injection and detection parts are separated laterally, the shield-to-shield gap which corresponds to the head resolution can be reduced dramatically. For 5 Tb/in^2, it should be less than 13.5 nm. Image reproduced from [57].***

geometry, steady state magnetic oscillations at gigahertz frequencies. Such NSTOs have been proposed as a field source for microwave-assisted magnetic recording (MAMR) [65] where the high-frequency magnetic fields are used to resonantly excite the recording media and assist with the writing process. For magnetic sensor applications, the modulation in the oscillator's frequency when a magnetic field is applied is used to detect the field from data bits. This approach promises high data rates and suppresses noise arising from thermal fluctuations, enabling sub-20-nm sensors with high sensitivity [60]–[63].

As highlighted above, the development of spintronics and the magnetoresistive read head for hard disk drives has had a dramatic impact on the evolution of the hard disk drive and digital storage. The introduction of the magnetoresistive read head has corresponded with a dramatic increase in storage densities over the last two decades, leading to significant decreases in cost that ushered in the age of digital storage. What is particularly evident is the continued emergence of new spintronic phenomena and device structures that have enabled the evolution of the hard drive from AMR, to GMR and to TMR read heads, as well as to new approaches such as CPP–GMR, nonlocal spin devices, or spin-torque oscillators for the future. While solid state drives based on semiconductor flash memory are increasingly used in high-performance applications and new storage technologies are being explored, there will be continued need for the massive and cost-effective storage capacity that is currently achieved in magnetic hard drives.

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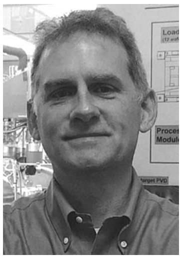

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