The Era of Giant Magnetoresistive Heads

By Jim Belleson and Ed Grochowski

Hitachi's magnetoresistive and giant magnetoresistive head technologies enable data storage products with the industry's highest areal densities.

Introduction

Magnetic hard disk drives (HDDs) continue to be the primary, high performance storage technology in terms of bytes shipped per year. The success of HDDs originates from an ever increasing demand for storage capacity coupled with a consistent reduction in price per megabyte. Areal density (expressed as billions of bits per square inch of disk surface area, Gbits/in^2) is the product of linear density (bits of information per inch of track) multiplied by track density (tracks per inch), and varies with disk radius. It is often valuable to quote areal density in terms of its maximum value. Improved areal density levels have been the dominant reason for the reduction in price per megabyte. Figure 1 shows the 60% compound annual growth rate (CGR) in areal density for Hitachi HDD products. If this CGR continues, areal densities of 10 Gbits/in^2 and 40 Gbits/in^2 are expected by the years 2001 and 2004 respectively. High areal densities have been achieved by introducing new technology and by proportionally reducing certain key dimensions within the HDD ("scaling"). The most significant advancements have been the magnetoresistive (MR) head, the extended magnetoresistive head (MRx) head, and the follow-on giant magnetoresistive (GMR) head technologies.

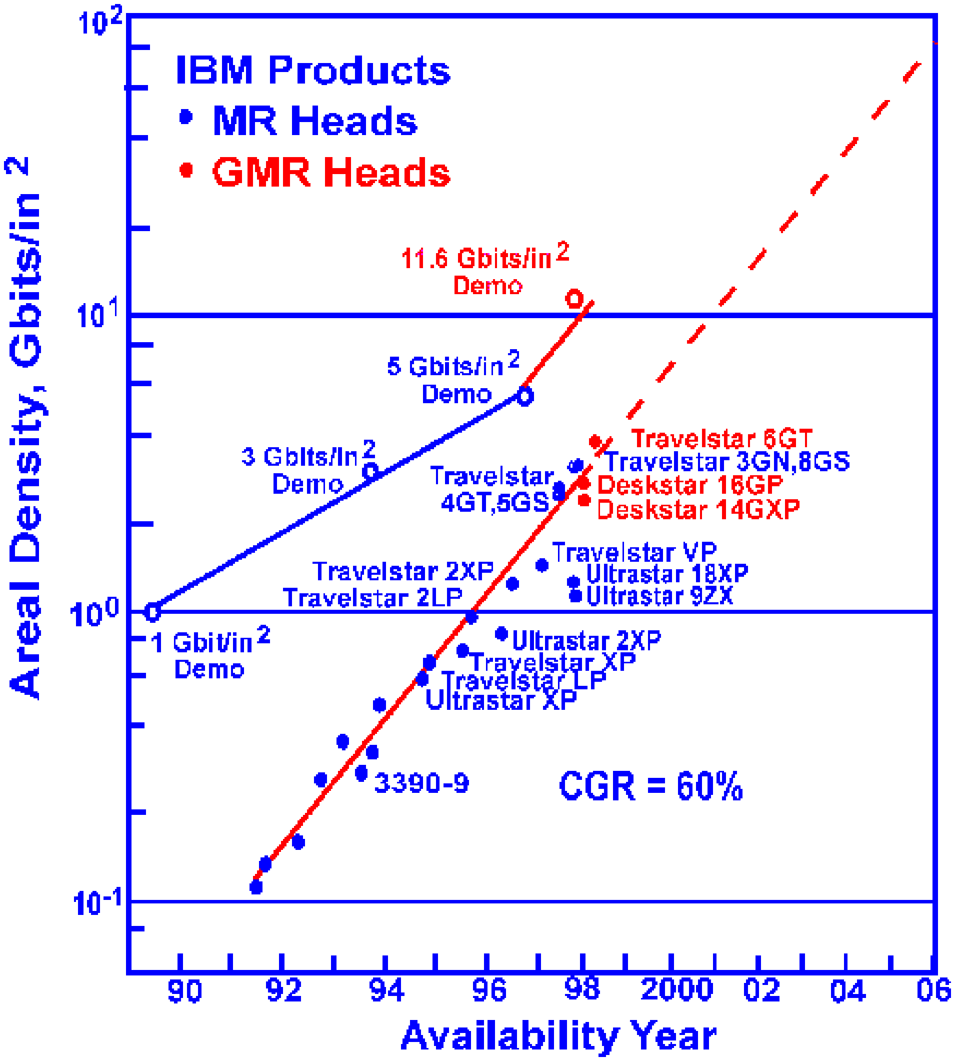

Figure 1. Areal density perspective.

In 1991, IBM pioneered the use of MR heads for disk drives with the 1 Gigabyte (GB), 3.5-inch IBM 0663-E12 drive, which provided the highest areal density available at the time. In 1994, using MR heads, IBM Research demonstrated an areal density of 3 Gbits/in^2 and about 3 years later, in 1997, IBM started manufacturing 3 Gbits/in2 MR heads in volume. In 1996, IBM Research demonstrated an areal density of 5 Gbits/in^2 using an advanced MR head1. It would be expected that laboratory investigations continue at IBM to achieve even higher areal densities using more advanced head designs, i.e. GMR.

The GMR effect was discovered in 1988 in perfect-crystal samples exposed to very high fields (1000 times the fields used in HDDs)[2]. In that same year an initial concept for using the GMR effect in magnetic recording was disclosed3. By 1991, work at IBM's Almaden Research Center opened the door for affordable applications by showing the spectacular GMR effect could also be achieved in more-easily-made sputtered, polycrystalline multilayer samples. By 1991 IBM Research also developed GMR structures, named "spin valves", that responded to the much smaller magnetic fields produced by written data in a HDD4. In 1994, IBM Research announced it had created the world's most sensitive sensor for detecting computer data on magnetic hard disks using the GMR effect5. In December 1997, IBM announced a 16.8 Gbyte 3.5-inch HDD product using GMR heads for the high performance desktop market, the industry's first GMR storage product and with an areal density of 2.69 Gbits/in^2 , the highest for that form factor. In early 1998 IBM announced and began production of a 6.48 Gbyte 2.5-inch HDD designed for the mobile computer market with an areal density of 4.10 Gbits/in^2 using GMR heads, another industry first. Concurrent with this, IBM announced that a GMR spin valve head with an areal density capability of 11.6 Gbits/in^2 was under investigation, and that this advanced head was produced using much of the existing processing facilities available for today's production heads6.

The primary advantage of GMR heads is greater sensitivity to magnetic fields from the disk. This increased sensitivity makes it possible to detect smaller recorded bits and to read these bits at higher data rates. Larger signals from GMR heads also help overcome electronic noise. GMR heads are expected to support areal densities beyond 11.6 Gbits/in^2 and it is projected that GMR will become the dominant head technology for the years beyond 2000.

The high areal densities attainable with MR and GMR heads enable disk drive products to offer a maximum storage capacity with a minimum number of components — heads and disks. Fewer components translates to lower storage costs, higher reliability, and lower power requirements.

In 2003, Hitachi Global Storage Technologies was founded as a result of the strategic combination of IBM and Hitachi’s storage technology businesses and technologies, such as giant magnetoresistive heads.

Hitachi Global Storage Technologies continues to lead the industry in areal density advancements. This leadership is due to extensive research and development efforts at Hitachi's Almaden Research Center in San Jose combined with the ability to ramp this technology quickly in manufacturing facilities around the world.

Merged Read/Write Head — A Proven Design

The head design consists of a thin film inductive write element and a read element (Figure 2). The read element consists of an MR or GMR sensor between two magnetic shields. The magnetic shields greatly reduce unwanted magnetic fields coming from the disk; the MR or GMR sensor essentially "sees" only the magnetic field from the recorded data bit to be read. In a merged head the second magnetic shield also functions as one pole of the inductive write head.

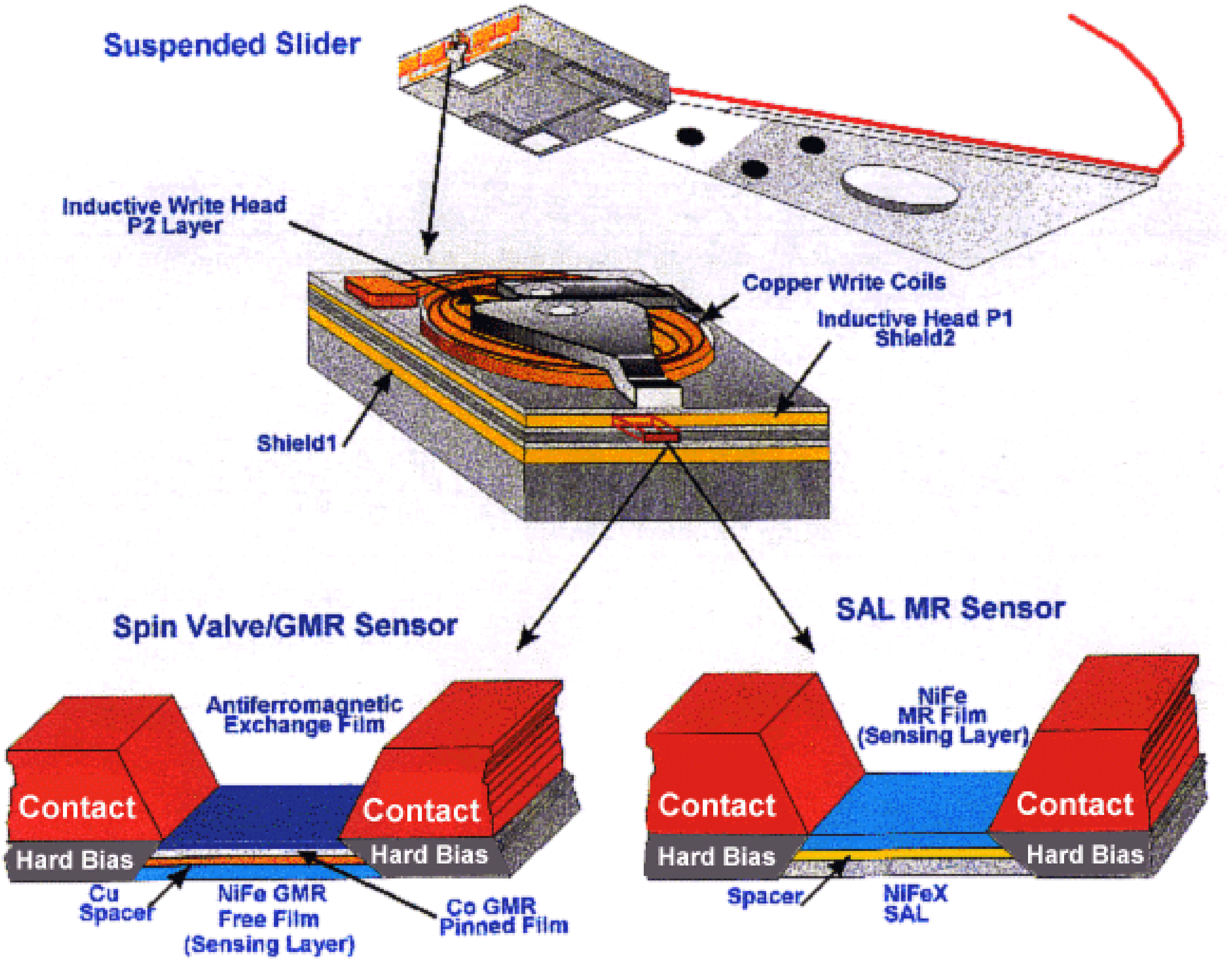

Figure 2. MR and GMR head structures.

The advantage of separate read and write elements is both elements can be individually optimized. A merged head has additional advantages. This head is less expensive to produce, because it requires fewer process steps; and, it performs better in a drive, because the distance between the read and write elements is less.

Magnetic Recording Process

Figure 3 depicts a merged read/write head flying over a rotating disk. The inductive write head records bits of information by magnetizing tiny regions along concentric tracks. During reading, the presence of a magnetic transition or flux reversal between bits, causes the magnetic orientation in the MR or GMR sensor to change. This in turn, causes the resistance of this sensor to change. The sensor's output voltage or signal is the product of this resistance change and the read bias current. This signal is amplified by low-noise electronics and sent to the HDD's data detection electronics.

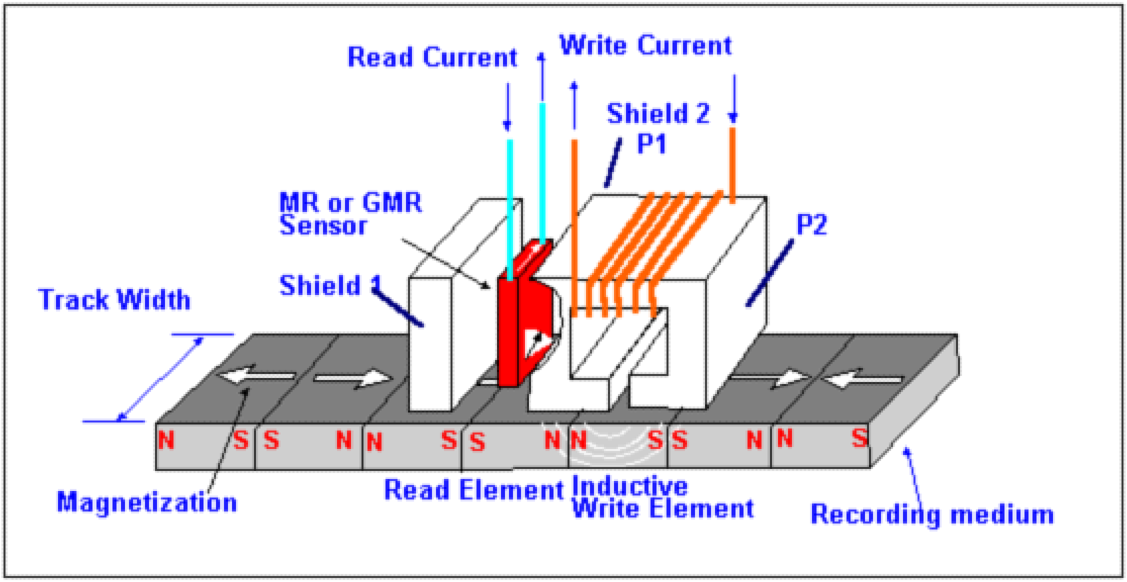

Figure 3. Magnetic recording process.

MR And GMR Sensor Technology

HDD designers now have access to MR and GMR sensors, which are both very thin. If 250,000 of these sensors, excluding leads, were stacked on top of each other, the stack would be less than one inch high. The biggest functional difference between MR and GMR sensors is sensitivity, measured by percent change in resistance. In an MR sensor a resistance change is caused by an intrinsic property of the sensing layer. In a GMR sensor, however, a resistance change is caused by the quantum nature of electrons. Figure 4 shows the sensitivity of GMR sensors is more than twice the sensitivity of MR sensors.

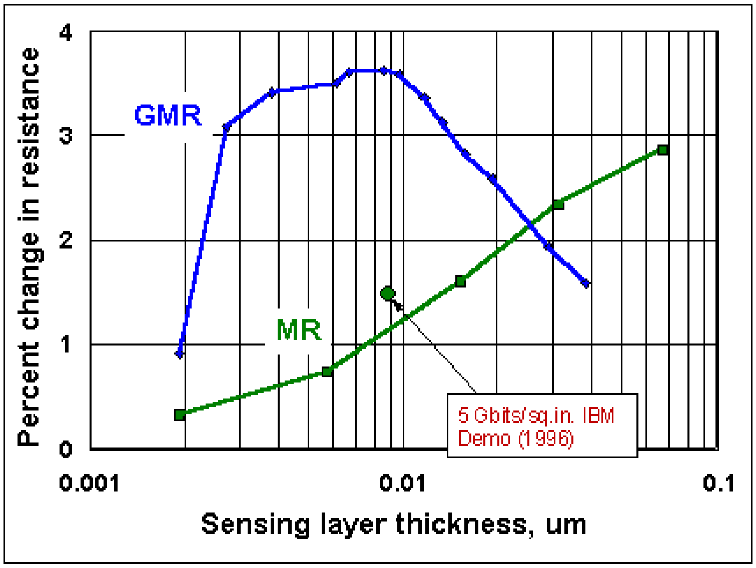

Figure 4. Percent change in resistance of MR and GMR sensors

MR and GMR sensors are composed of multiple thin films (Figures 2, 5, and 6.). Both sensors have a sensing layer which responds to external magnetic fields. In the absence of an external magnetic field, this sensing layer will spontaneously magnetize itself parallel with the long axis of this layer, which is parallel to the disk. A fixed magnetic field ("horizontal bias") is also applied in this direction by hard bias films to establish a single magnetic domain in the sensing layer. This single magnetic domain minimizes domain noise and promotes consistent reading. This sensing layer's magnetic orientation, referenced to the disk, rotates from parallel to perpendicular when an increasing perpendicular magnetic field ("transverse magnetic field") is applied. This field is composed of a varying external magnetic field from the rotating disk and fixed internal magnetic fields ("transverse bias") from other parts of the sensor.

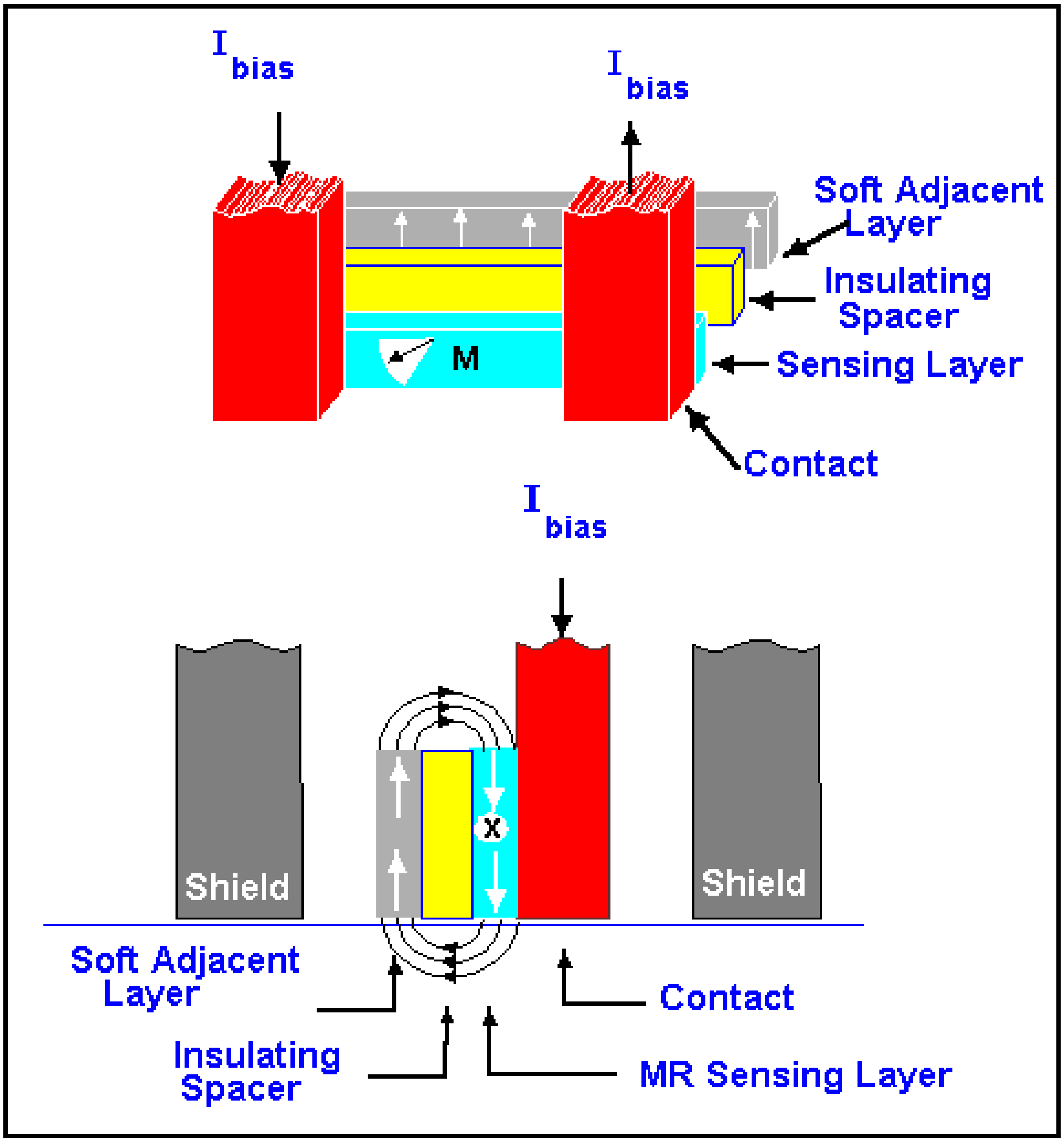

Figure 5. MR head basics.

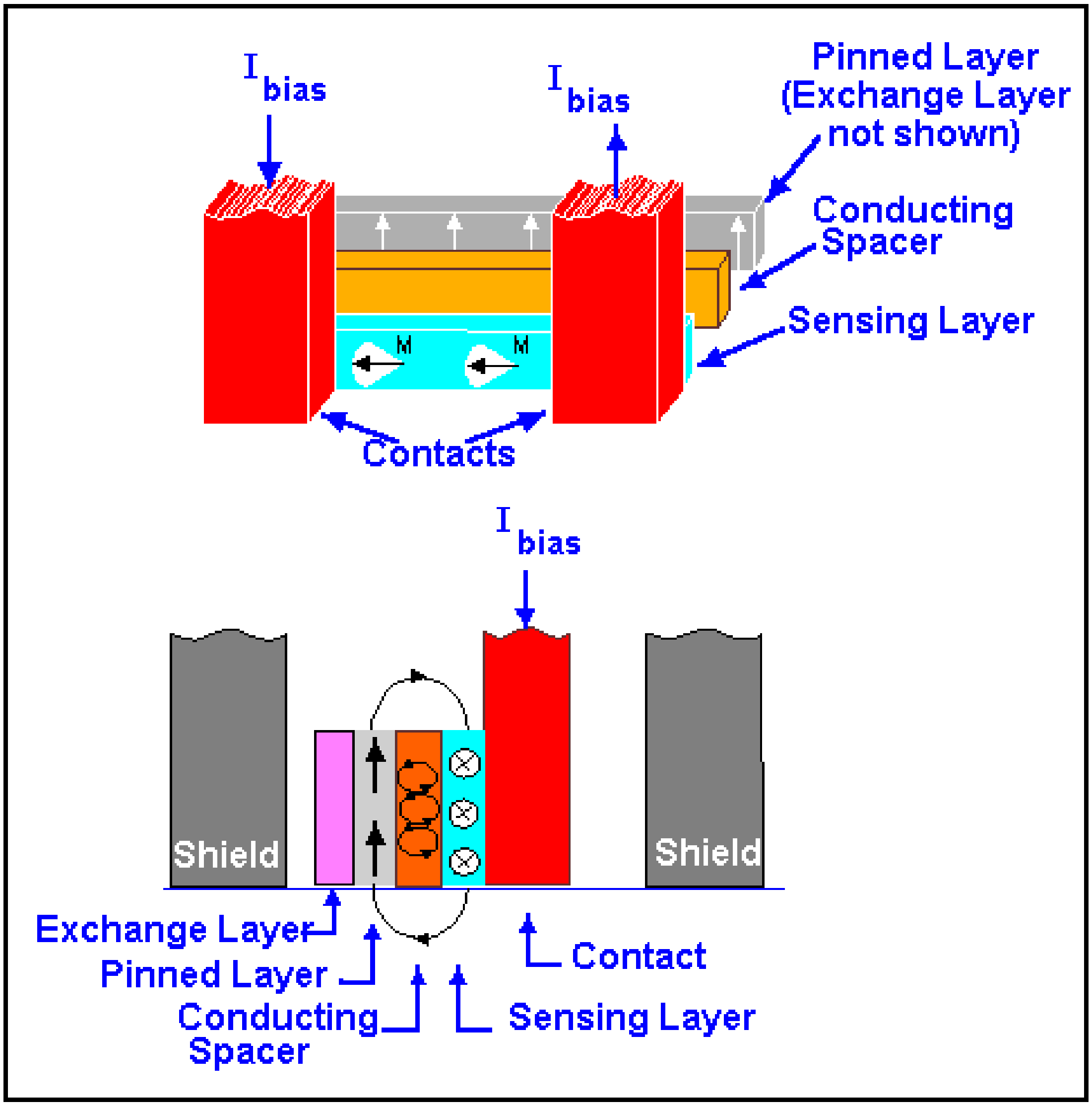

Figure 6. GMR head basics.

MR Sensor Basics

In a typical MR material, e.g. a nickel-iron alloy, conduction electrons move less freely (more frequent collisions with atoms) when their direction of movement is parallel to the magnetic orientation in the material- the "MR effect". When electrons move less freely in a material, the material's resistance is higher.

The MR sensor's sensing layer is MR material. When no transverse magnetic field is applied, this sensing layer's magnetic orientation is parallel to the disk and to the electron flow; therefore, the resistance of the sensing layer is higher. A transverse magnetic field can then rotate the sensing layer's magnetic orientation producing lower resistance (Figure 7). However, equal positive or negative values of transverse magnetic field will produce the same sensing layer resistance. To avoid this ambiguity, transverse bias is applied to keep the transverse magnetic field always positive or always negative. Hitachi has developed a unique, patented soft-adjacent layer (SAL) structure that provides transverse bias.

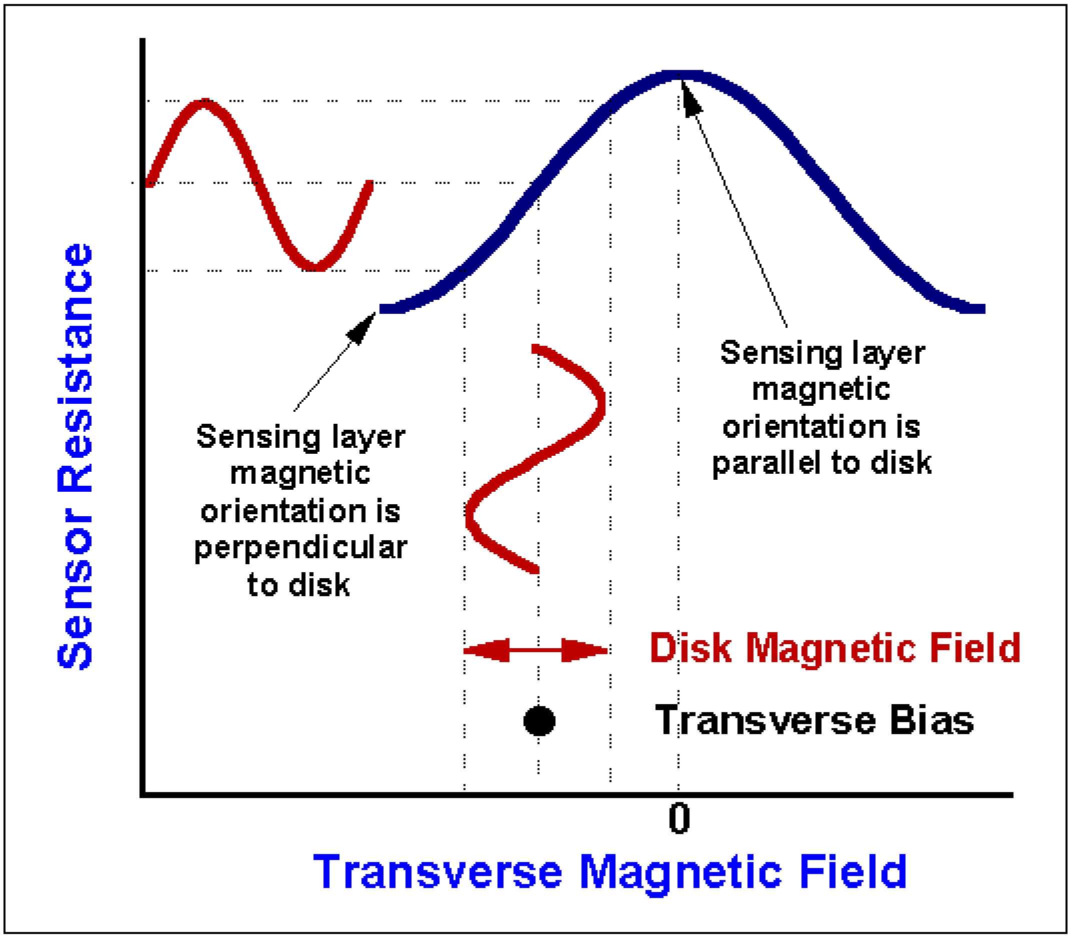

Figure 7. MR sensor response to disk magnetic field

GMR Sensor Basics

Hitachi has developed GMR sensors composed of four thin films: a sensing layer, a conducting spacer, a pinned layer, and an exchange layer. The first three of these films are very thin, allowing conduction electrons to frequently move back and forth between the sensing and pinned layers via the conducting spacer. The magnetic orientation of the pinned layer is fixed and held in place by the adjacent exchange layer, while the magnetic orientation of the sensing layer changes in response to the magnetic field from the disk. As explained below, a change in the magnetic orientation of the sensing layer will cause a change in the resistance of the combined sensing and pinned layers.

GMR sensors exploit the quantum nature of electrons, which have two spin directions — spin up and spin down. Conduction electrons with a spin direction parallel to a material's magnetic orientation move freely, producing low resistance. Conversely, conduction electrons with spin direction opposite to the material's magnetic orientation are hampered by more frequent collisions with atoms in the material, producing higher resistance.

The application of this quantum nature of electrons to a GMR sensor is shown in Figure 8. Lower resistance occurs when the sensing and pinned layers are magnetically oriented in the same direction, since electrons with spin direction parallel to this magnetic orientation move freely in both films. Higher resistance occurs when the magnetic orientations of the sensing and pinned layers oppose each other, because the movement of spin up electrons is hampered by one of these magnetic layers and the movement of spin down electrons is hampered by the other layer. The resistance of the sensing layer is also changed by the MR effect, however the GMR effect is dominant. Figure 9 illustrates the GMR sensor's response to a changing transverse magnetic field. To realize the full sensitivity of a GMR sensor, the transverse magnetic field variations must fully utilize the linear portion of the GMR sensor's response curve, as shown in Figure 9. This is accomplished by either changing the slope of this response curve or by adjusting the amplitude of the transverse magnetic field. The slope of this response curve can be changed by changing the thickness of the sensing layer and the amplitude of the transverse field can be changed by reducing the magnetic field from the disk. (The same applies to MR sensors.)

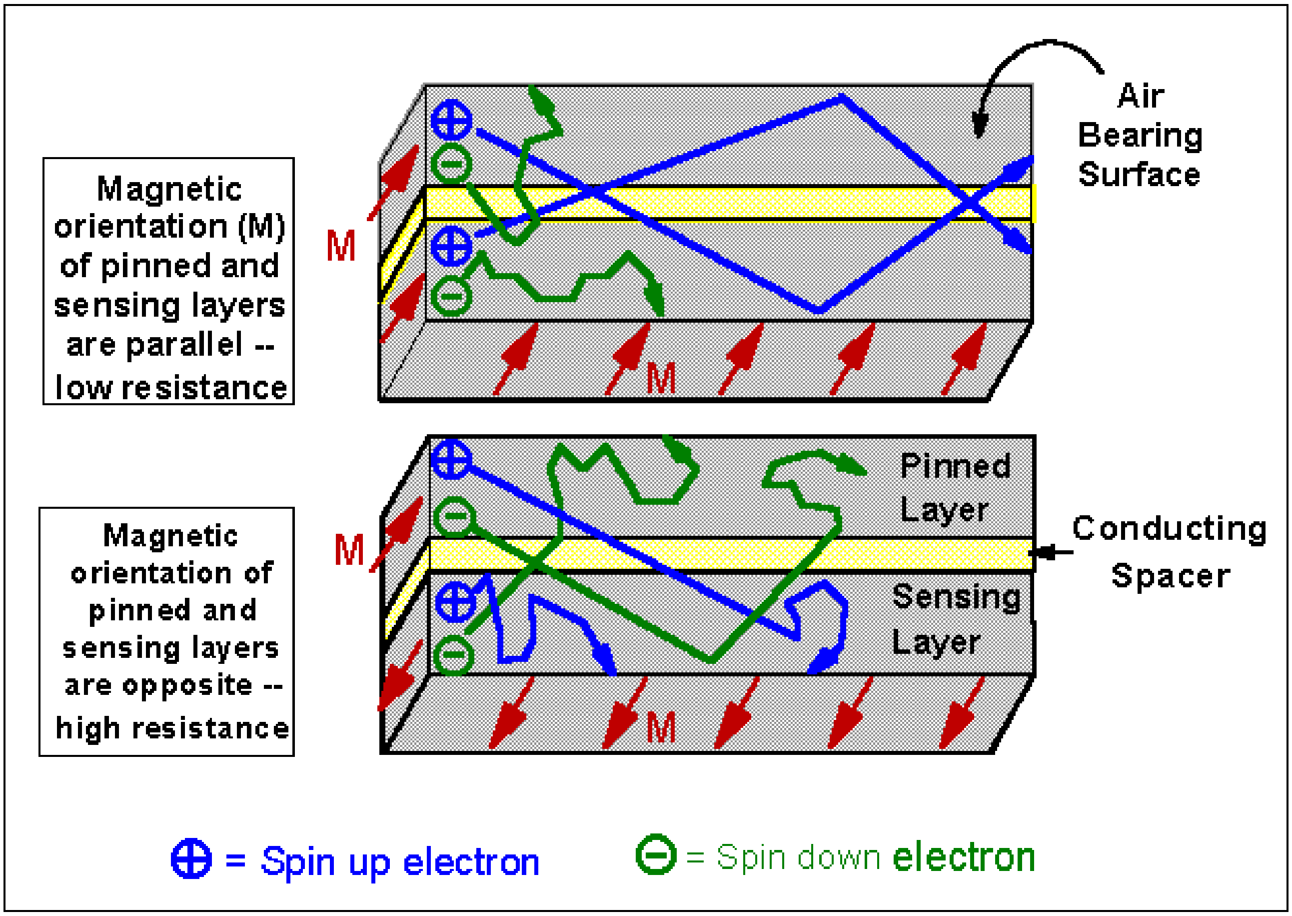

Figure 8. GMR sensor basics

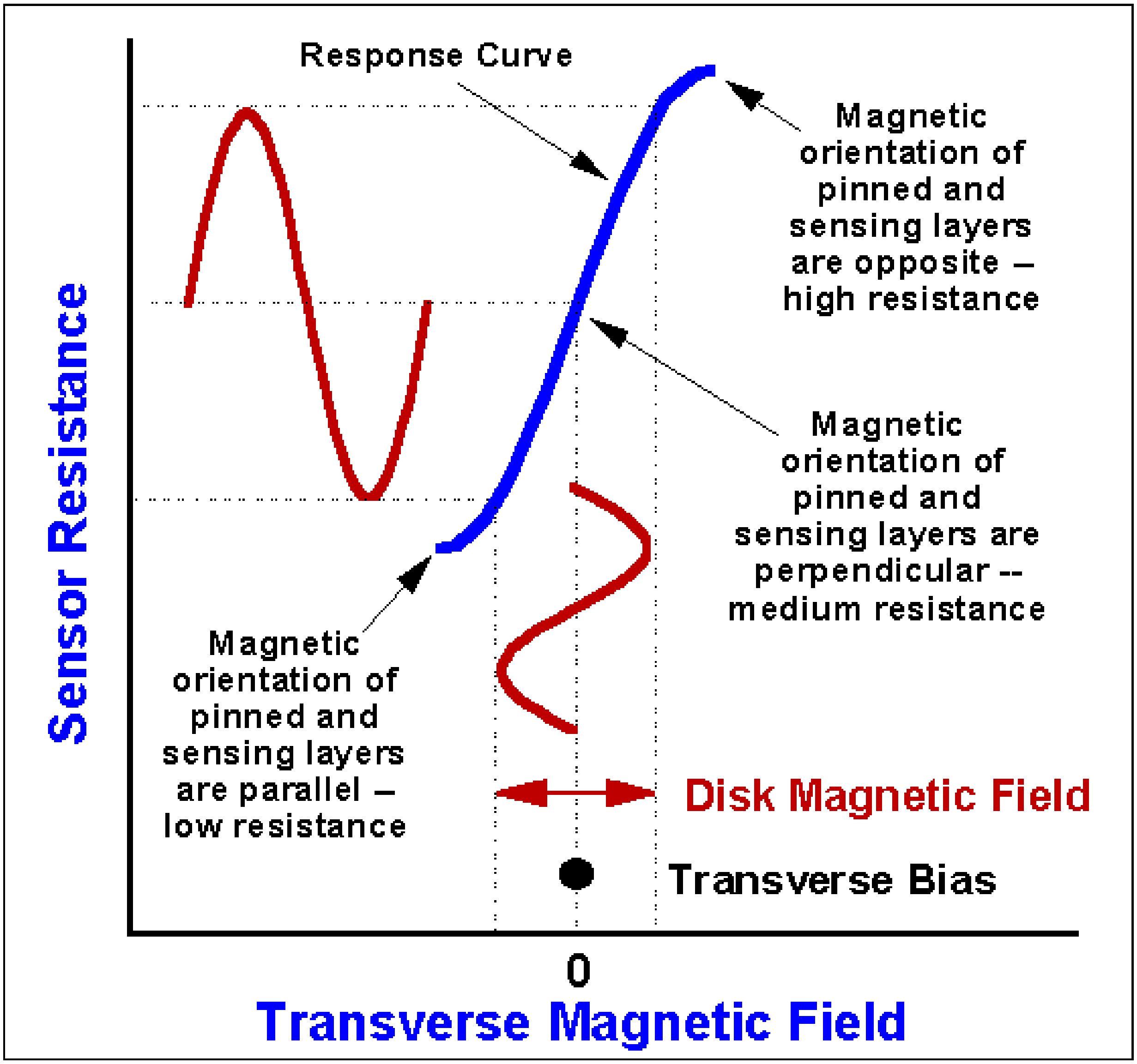

Figure 9. GMR sensor response to disk magnetic field

Extension of GMR beyond 10 Gbits/in²

For 10 Gbits/in² and beyond, GMR sensors will need to be thin enough to fit within the required read gap (gap between the shields) and sensitive enough to detect the magnetic fields from written bits of information at these densities. From previous MR head designs, the maximum sensor thickness for 2.6 Gbits/in² is 0.08 microns, and the recorded bit length is 0.12 microns. The maximum length of the read gap is about twice the recorded bit length for a partial response detection channel (PRML)., and the maximum thickness of the MR or GMR sensor is 1/3 the read gap length to allow separation of the sensor and shields. If the current ratio of bit density to track density is maintained, it is estimated by scaling that the maximum sensor thickness for 10 Gbits/in² and 40 Gbits/in² will be roughly 0.04 and 0.02 microns respectively. Experimental GMR sensors are thin enough to fit into this 10 Gbits/in² read gap; however, a more advanced sensor may be required to fit into a 40 Gbits/in² read gap. If track density advances more rapidly than bit density, the maximum sensor thickness for higher areal density heads can be relaxed. If everything scales, simple calculations suggest the percent change in resistance of a sensor needs to increase proportional to the square root of the areal density, assuming constant surface velocity and sensor temperature7. Therefore, it will be necessary to continue to improve GMR sensitivity as areal densities increase. In the design of a recording system, involving many head, disk, flying height, and channel tradeoffs, high sensitivity GMR heads can be used in many ways to enhance areal density and data rate. It is expected that advancements in head technology will continue to meet future areal density requirements, as illustrated in Figure 10.

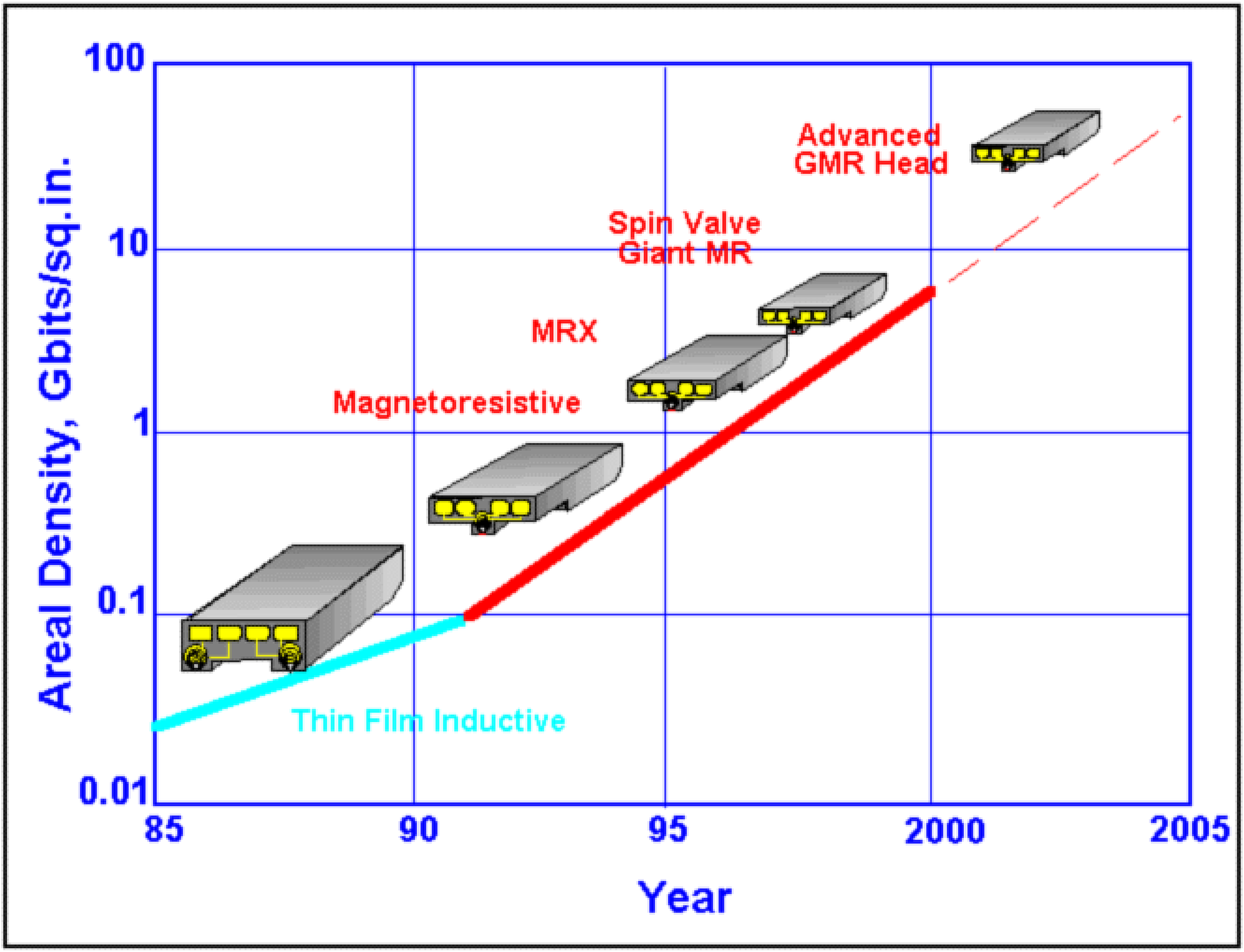

Figure 10. Magnetic head evolution

Manufacturing Considerations- MR Head Experience Pays Off

The GMR heads used in Hitachi's 11.6 Gbit/in² demonstration closely resemble heads currently being manufactured by Hitachi in high volumes, both MR and GMR, except certain dimensions are smaller. Since this demonstration head was produced using some actual manufacturing processes, it is likely that advanced GMR heads can be manufactured with higher areal densities than currently available in the marketplace. As future areal densities and internal data rates increase, it will be necessary to evolve production from MR to the more sensitive GMR heads. Fortunately, a majority of the manufacturing processing and testing tools are common to both MR and GMR heads. With this commonality, the years of experience gained manufacturing MR heads is being directly applied to manufacturing GMR heads.

MR and GMR head processing requires photolithography to define the head structure; e.g. the features that determine the track width seen by the read head ("read track width"). The nominal MR read track width were 2/3 of the track pitch to accommodate tolerances for head width. track-to-track spacing, and track following, a 2.6 Gbits/in^2 (12,500 tracks/in.) HDD would require a 1.33 micron read track width. Using this estimate, the required read track widths for 10 Gbits/in^2 and 40 Gbits/in^2 is 0.68 and 0.34 microns, respectively. In addition to satisfying these read track width requirements, the photolithography must have sufficient depth of field to accurately define any non-planar head features in a merged read and write head. Fortunately, with the semiconductor industry's emphasis on higher density integrated circuits, we expect the capability of projection photolithography, with possibly a few enhancements, will be adequate to support the projected areal density growth in HDDs.

MR and GMR head manufacturing also requires precision deposition tools to control film thickness. The films used in the GMR sensor are very thin and the tolerances are tight; e.g. a copper conducting spacer is less than 15 atomic layers thick. GMR heads also contain thin film materials which require precise process control to achieve compositional uniformity.

These manufacturing challenges are being addressed now, so the transition from MR to GMR will be well underway by the year 2000. The basic GMR structure used will continue to follow the IBM-developed spin valve concept for this future progress.

Summary

GMR heads are starting to be used in HDD products, because more sensitive heads are needed to maintain high quality read-back signals, as areal densities and data rates increase. GMR technology is an evolutionary step from today's MR heads and this technology will utilize much of the design, production, and test experience associated with MR heads. GMR heads are expected to support areal densities well beyond 10 Gbits/in^2; however, as areal densities continue to grow, more advanced structures beyond GMR may be required. Manufacturing challenges will continue to involve tight control of critical dimensions, film thickness and film compositions. Continued advancements in head technology are essential to maintain rapid areal density growth during the next decade, and GMR spin valve heads have been shown to have the ability to meet future areal density requirements. Truly, the era of GMR heads for magnetic storage has begun.

References

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