Low-Field Magnetic Sensing with GMR Sensors

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Abstract -- Industry continues to reap the benefits of solid state magnetic field sensing. Every day new applications are found for solid state magnetic field sensors due to their small size, low power. And relatively low cost. The new frontier for these solid state sensors is very low magnetic fields; the kinds encountered when looking for geophysical anomalies, either natural or man-made, various physiological functions, metal defects, magnetic ink and minute magnetic particles associated with immunoassay. In the past, equipment to perform many of these functions has required a substantial amount of power and has been quite large. In addition, because of their size, the equipment has become costly. Leveraging on substantial government efforts, GMR technology is being applied to these applications today and the newer GMR technologies such as Spin Dependent Tunneling (SDT) will make even more of these applications possible. As with all of solid state technology, many of the now difficult measurements will become more commonplace and provide the ingredients for more precise measurement, diagnosis, and control. Several applications will be presented on the use of individual sensors and arrays being used to address some of these new areas.

INTRODUCTION

Magnetic field sensing in industry is often utilized for control and measurement purposes – linear and rotary position sensing, gear tooth sensing, and current sensing.[1] In these applications, relatively large magnetic fields are used to avoid confusion with background magnetic fields such as the Earth's magnetic field, fields from ferromagnetic objects, and EMI. The fields detected are provided either from permanent magnets or from currents in coils, sometimes with soft magnetic cores. The size of these magnetic fields is usually tens to hundreds of oersteads (One Oe equals approximately 80 A/m.) Since magnetic field sources are inherently dipole in nature, they decrease with the inverse cube of distance. Therefore, the fields from these sources are relatively localized.

Despite the increased measurement difficulties encountered with low fields, magnetic fields of less than an Oe are gaining increasing attention in industry. Compassing applications detect the components of the Earth's magnetic field (less than one-half Oe) to determine direction relative to magnetic North. Sensitive instruments which measure magnetic fields or magnetic field gradients can detect the small magnetic fields at considerable distances from soft magnetic materials magnetized by the Earth's magnetic fields. These objects include motor vehicles, buried iron surveying stakes, and lost wrenches. There are other objects which produce very small magnetic fields because they are small themselves. The black ink in many currencies and other negotiable documents contains small magnetic particles which act as dipoles. Denomination determination and currency validation can be based on the magnetic signature of a bill passed close to a magnetic sensor. The more sensitive the sensor, the larger the allowable head-to-sensor gap. Eddy current sensing to detect flaws in conducting materials or even differing conductivity in the soil requires high-frequency, low-field sensors.

Solid state magnetic field sensors have an inherent advantage in size and power when compared to search coil, flux gate, and more complicated low-field sensing techniques such as Superconducting Quantum Interference Detectors (SQUID) and spin resonance magnetometers. A solid-state magnetic sensor directly converts the magnetic field into a voltage or resistance with, at most a dc current supply. The sensing can be done in an extremely small, lithographically patterned area further reducing size and power requirements. The small size of a solid state element increases the resolution for fields that change over small distances and allows for packaging arrays of sensors in a small package. Figure 1 shows a comparison in cost and power of several low field sensors all designed with the same minimum field resolution limited by thermal noise, 10^{-8} Oe/√Hz.

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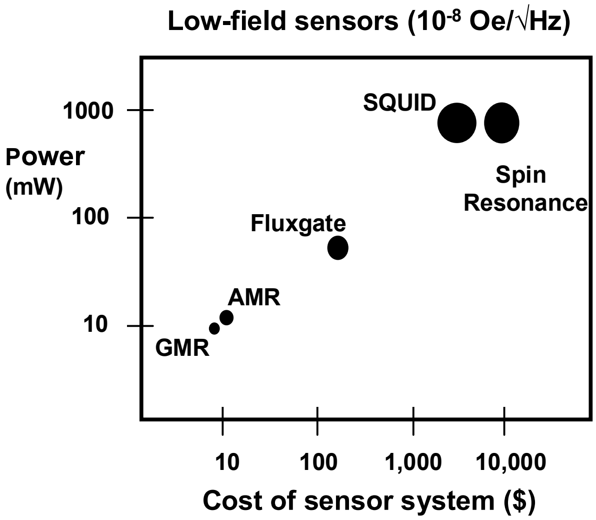

Figure 1. Comparison of several low-field magnetic sensor technologies. Power and cost indicated for each sensor. Size of circle indicates relative size.

GMR TECHNOLOGY

Recent developments in thin-film magnetic technology have resulted in films exhibiting a large change in resistance with magnetic field. This phenomenon is known as giant magnetoresistance (GMR) to distinguish it from conventional anisotropic magnetoresistance (AMR). Whereas AMR resistors exhibit a change of resistance of less than 3 %, various GMR materials achieve a 10 to 20 % change in resistance. GMR films have two or more magnetic layers separated by a non-magnetic layer. Due to spin-dependent scattering of the conduction electrons, the resistance is maximum when the magnetic moments of the layers are antiparallel and minimum when they are parallel. Various methods of obtaining antiparallel magnetic alignment in thin ferromagnet-conductor multilayers are discussed elsewhere.[2,3,4] A brief overview is given in the section on GMR sensors below. The structures currently being used in GMR sensors are unpinned sandwiches, antiferromagnet pinned spin valves, and antiferromagnetic multilayers. Spin valves are gaining considerable interest for use as magnetic read heads in computer hard disks.[5]

Spin dependent tunneling (SDT) structures also exhibit GMR. In these structures an insulating layer separates two magnetic layers. The conduction is due to quantum tunneling through the insulator. The size of the tunneling current between the two magnetic layers is modulated by the direction between the magnetization vectors in the two layers. The conduction path must be perpendicular to the plane of the GMR material since there is such a large difference between the conductivity of the tunneling path and that of any path in the plane. Extremely small SDT devices several μm on a side with high resistance can be fabricated using photolithography allowing very dense packing of magnetic sensors in small areas. These recent materials are a topic of considerable research. Values of GMR of 10 to 30 % have been regularly observed. The saturation fields depend upon the composition of the magnetic layers and the method of achieving parallel and antiparallel alignment. Values of saturation field range from 0.1 to 10 kA/m (1.25 to 125 Oe) offering the possibility of extremely sensitive magnetic sensors. The insulating, tunneling layer provides inherently high resistance sensors suitable for battery operation.

MAGNETIC FIELDS IN INDUSTRY AND MEDICINE

There are many places in industry and in medicine in which magnetic fields the size of the Earth's magnetic field and smaller are of interest. The source of these fields can be magnetized objects, electrical currents, or the Earth's field itself. The low-field aspect of these applications can be due to the distance to a magnetic object or the size of the magnetic object itself. All magnetic sources produce a magnetic dipole field if the observer is at a distance from the source. Dipole fields decrease as the inverse cube of the distance from the source. They are also proportional to the volume of the source and to the maximum magnetization at the source. A magnetized cylinder whose diameter and length are one-half those of a larger cylinder at any distance will have a magnetic field 1/8 as strong as the field from the larger cylinder. In addition, doubling the distance from a magnetized cylinder will decrease the field to 1/8 the field at the original position. Distance and miniaturization lead to low fields.

Objects made from soft magnetic materials are easily magnetized by relatively small magnetic fields including the Earth's magnetic field. These objects can be as simple as small iron pipes used as surveying markers or entire automobiles and trucks. In one case the object is to locate a buried object from a distance, in the other to detect the presence or passage of a vehicle from up close. In both cases the smaller the field detected, the more useful the sensor. In both cases the field detected must be separated from the Earth's magnetic field which may be stronger than the field of interest. Various methods are used to subtract the Earth's magnetic field. Since the Earth's magnetic field is relatively constant, it can be subtracted out for applications in which the sensor is stationary. In applications for which the field of interest is time varying, the constant Earth's field can be subtracted or filtered out. When looking for a magnetic dipole which is fixed relative to the Earth, two sensors separated by a distance can be used as a field gradient sensor. The dipole field from the object sought will have a larger field gradient than that from the Earth whose center is several thousand miles away. Low-field magnetic sensors and magnetic field gradient sensors can also be used to locate magnetized objects or even holes in ferromagnetic plates behind concealing non-magnetic sheets. An extension of the same principle is the location of unexploded munitions (UXO) using magnetic sensors and arrays of magnetic sensors.

Even non-magnetic metals can be detected using magnetic sensors by the use of eddy currents. An ac magnetic field generated by a current in a coil causes eddy currents in the conducting material which oppose the applied field. A magnetic field sensor can detect the difference between the field with and without the conducting material present. The sensor can be located in an orientation such that its sensitivity does not lie in the direction of the field generated by the coil. The presence of a conducting material, or even the existence of a crack or flaw in the conducting material, can change the direction of the magnetic field enough that the sensor will now detect a magnetic field. This same general principle can be used for subsurface geophysical exploration.[6] Changes in conductivity of the soil due to water can be detected using eddy current techniques as can buried conducting pipes or even non-conducting pipes containing water.

Small magnetic fields are also produced by magnetized small particles of iron oxide commonly used in black ink. These small fields can produce signatures when read by magnetic sensors that can be used to identify the denominations of currency presented to vending machines. The signature of additional magnetic information encoded into many counties' currencies can be used to distinguish valid currency from copies. In the past inductive recording heads pressed in contact with the bills have been used in this application. The magnetic fields involved are less than 0.1 Oe (8 A/m) at the surface of the bill and decrease rapidly with distance. To avoid bills jamming in the pathway, a non-contact magnetic sensor is preferred. GMR sensors have been used to obtain signatures up to 2 mm from the bill. It must be pointed out that the greater the sensor to bill distance, the larger the minimum feature size that can be detected. Another financial applications in which small magnetic fields are detected is the reading of the Magnetic Ink Character Recognition or MICR magnetic numbers on the bottom of checks. These stylized MICR numbers each produce a unique magnetic signature when the checks are sorted at high speeds.

Medical applications that involve detecting small magnetic fields include the monitoring of magnetic fields from physiological functions. Nerve impulses are electrical currents. These currents create magnetic fields. Monitoring nerve signals by detecting the magnetic fields is less invasive, and more reliable than implanting electrodes to pick up voltage signal. Relatively large and cumbersome magnetometers such as SQUIDs are used for monitoring magnetic signals for studies such as magneto-encephalographs. Improved solid state magnetic sensors will allow smaller sensors that can be placed closer to the source of the magnetic fields resulting in larger signals.

Monitoring the position of parts of the body, especially the head, is important to various medical studies. It is also used in virtual reality and heads-up targeting. Three-axis magnetic sensors attached to the body part in question detect the components of the Earth's magnetic field. From this information the orientation relative to the Earth's field can be calculated. By adding accelerometers the actual position can be calculated.[7]

Rapid, portable biosensors that measure the presence of DNA or antibodies are a recent area of research using low-field magnetic sensors.[8] Small magnetic beads coated with biological molecules are allowed to settle on substrate with substance which bond to specific molecules of interest. After removing the beads that are not bonded to the substrate, the presence of the remaining magnetic microbeads is detected by magnetic sensors. Several bioassays can be simultaneously accomplished using an array of magnetic sensors, each with a substance that bonds to a different biological molecule. This application requires extremely small, low-power, low-field magnetic sensors.

GMR MATERIALS

As mentioned in an earlier section, GMR materials must have at least two separated ferromagnetic layers whose magnetization vectors can assume different, in-plane directions. Several of the various ways of achieving different directions in different layers are discussed below as are methods of using these materials in magnetic field sensors.

Unpinned sandwich GMR materials consist of two soft magnetic layers of iron, nickel and cobalt alloys separated by a layer of a non-magnetic conductor such as copper. With magnetic layers 4 to 6 nm (40 to 60 Å) thick separated by a conductor layer typically 3 to 5 nm thick there is relatively little magnetic coupling between the layers. For use in sensors, sandwich material is usually patterned into narrow stripes a few μm wide. The magnetic field caused by a current of a few mA per μm of stripe width flowing along the stripe is sufficient to rotate the magnetic layers into antiparallel or high resistance alignment. An external magnetic field of 3 to 4 kA/m (35 to 50 Oe) applied along the length of the stripe is sufficient to overcome the field from the current as well as any magnetic exchange interaction between the layers and rotate the magnetic moments of both layers parallel to the external field reducing the resistance. A positive or negative external field parallel to the stripe will both produce the same change in resistance. An external field applied perpendicular to the stripe will have little effect due to the demagnetizing fields associated with the extremely narrow dimensions of these magnetic objects. Therefore, these stripes effectively respond to the component of magnetic field along their length.

The characteristic value usually associated with the GMR effect is the percent change in resistance normalized by the saturated or minimum resistance. Sandwich materials have values of GMR typically 4 to 9 % and saturate with 2.4 to 5 kA/m (30 to 60 Oe) applied field. Figure 2 shows a typical resistance *vs.* field plot for sandwich GMR material.

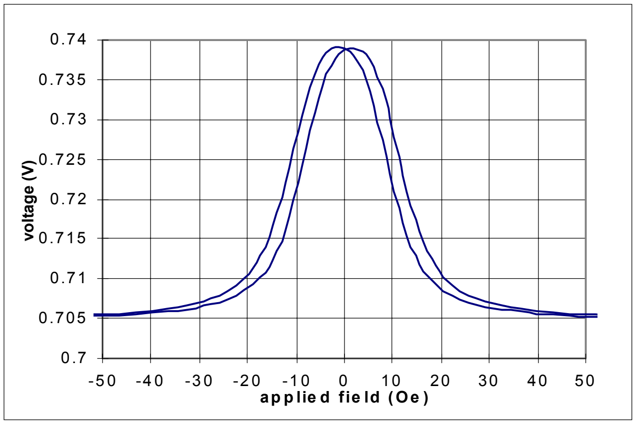

Figure 2. Voltage *vs*. applied field for a 2 μm wide stripe of unpinned sandwich GMR material with 1.5 mA current. GMR = 5 %.

Antiferromagnetic multilayers GMR materials consist of multiple repetitions of alternating conducting magnetic layers and conducting non-magnetic layers. Since multilayers have more interfaces than do sandwiches, the size of the GMR effect is larger. The thickness of the non-magnetic layers is less than that for sandwich material (typically 1.5 to 2.0 nm), and the thickness is critical. Only for certain spacer thickness will the polarized conduction electrons cause antiferromagnetic coupling between the magnetic layers. In the absence of an external magnetic field, each magnetic layer has its magnetic moment antiparallel to the moments of the magnetic layers on each side—exactly the condition needed for maximum spin dependent scattering. A large external field can overcome the coupling that causes this alignment and can align the moments so that all the layers are parallel—the low resistance state. If the conducting layer is not the proper thickness, the same coupling mechanism can cause ferromagnetic coupling between the magnetic layers resulting in no GMR effect.

A plot of resistance *vs*. applied field for a multilayer GMR material is shown in Figure 3. Note the higher GMR value, typically 12 to 16 %, and the much higher external field required to saturate the effect, typically 20 kA/m (250 Oe). Multilayer GMR materials have better linearity and lower hysteresis than typical sandwich GMR material.

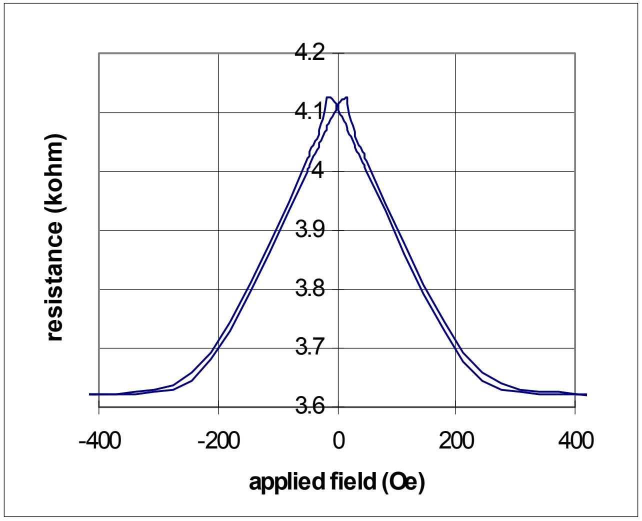

Figure 3. Resistance *vs*. applied field for a 2 μm wide stripe of antiferromagnetically coupled multilayer GMR material. GMR = 14 %.

Spin valves, or antiferromagnetically pinned spin valves, are somewhat similar to the unpinned spin valves or sandwich materials described earlier. An additional layer of an antiferromagnetic material is provided at the top or the bottom. The antiferromagnetic material such as FeMn or NiO couples to the adjacent magnetic layer and pins it in a fixed direction. The other magnetic layer is free to rotate. If the external magnetic field is applied in a direction parallel to the magnetization of the pinned layer, the change in sheet resistance from its high level for one field direction to a low level for the opposite field direction as is shown in figure 4. If the field is applied perpendicular to the pinned layer, the sheet resistance is minimum at zero field and increases for both positive and negative applied fields as is shown in figure 5. The maximum change in sheet resistance in this configuration is only one half of the total possible value. The free magnetic layer rotates from parallel to the pinned layer to perpendicular to it rather than from parallel to antiparallel.

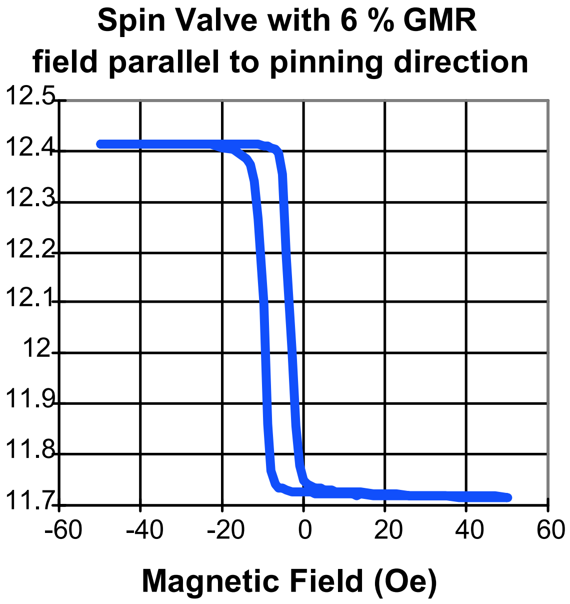

Figure 4. Sheet resistance *vs*. applied field for an anitferromagnetically pinned spin valve with the field applied parallel to the magnetization of the pinned layer. GMR = 6 %.

These materials do not require the field from a current to achieve antiparallel alignment or a strong antiferromagnetic exchange coupling to adjacent layers. The direction of the pinning layer is usually fixed by elevating the temperature of the GMR structure above the blocking temperature. Above this temperature, the antiferromagnet is no longer coupled to the adjacent magnetic layer. The structure is then cooled in a strong magnetic field which fixes the direction of the moment of the pinned layer. If the spin valve material is heated above its blocking temperature, it can loose its orientation. The operating temperature of a spin valve sensor is limited to below its blocking temperature Since the change in magnetization in the free layer is due to rotation rather than domain wall motion, hysteresis is reduced. Values for GMR are 4 to 20 % and saturation fields are 0.8 to 6 kA/m (10 to 80 Oe).

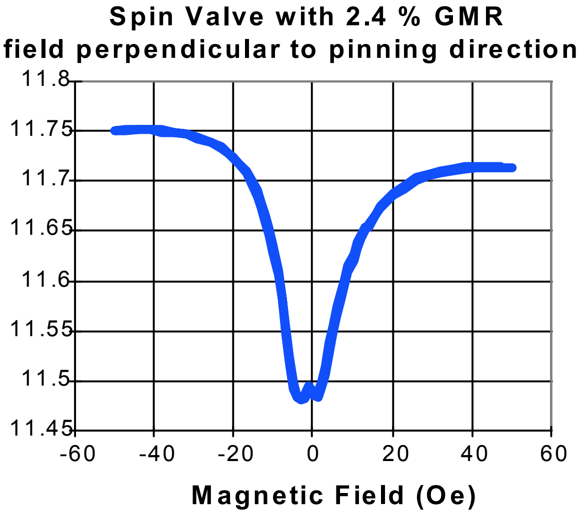

Figure 5. Sheet resistance *vs*. applied field for an anitferromagnetically pinned spin valve with the field applied perpendicular to the magnetization of the pinned layer. GMR = 2.4 %.

In order to obtain significantly higher sensitivities to magnetic fields, a new type of magnetoresistive material is being adapted to use in magnetic field sensors. This material exhibits a phenomenon called **Spin Dependent Tunneling** (SDT) which results in a change in effective resistance due to a change in the applied field.[9] The resistance *vs.* field effects are similar to the usual GMR spin valve effect, but larger. Sensors have been constructed from SDT material for use in low field applications which presently require fluxgate magnetometers. As with other GMR sensors they are very small (SOIC-8 package), require little power, and are easily combined with other electronics.

GMR SENSORS

Thin-film GMR materials deposited on silicon substrates can be fabricated into various configurations including resistors, resistor pairs or half bridges, and Wheatstone bridges. A sensitive bridge can be fabricated from four photolithographically patterned GMR resistors, two of which are active elements. The sheet resistance of these thin films is between 10 and 15 ohms per square. Resistors of 10 kΩ can be formed as 2 μm serpentine traces covering less than a 100 μm square. Small magnetic shields of permalloy plated over two of the four equal resistors in a Wheatstone bridge, the resistor connected to power on one side and the resistor connected to ground on the other side, protect these resistors from the applied field and allow them to act as reference resistors. Since they are fabricated from the same material, they have the same temperature coefficient as the active resistors. The two remaining GMR resistors are both exposed to the external field. The bridge output is therefore twice the output from a bridge with only one active resistor. The bridge output for a 10 % change in these resistors is approximately 5 % of the voltage applied to the bridge.

Additional permalloy structures plated onto the substrate can act as flux concentrators to increase the sensitivity. The active resistors are placed in the gap between two flux concentrators as is shown in Figure 6. These resistors experience a field that is larger than the applied field by approximately the ratio of the gap between the flux concentrators, D1, to the length of one of the flux concentrators, D2. In some sensors the flux concentrators are also used as shields by placing two resistors beneath them as is shown for R3 and R4. The sensitivity of a GMR bridge sensor can be adjusted in design by changing the lengths of the flux concentrators and the gap between them. In this way, a GMR material that saturates at approximately 300 Oe can be used to build different sensors which saturate at 15, 50, and 100 Oe. To produce sensors with even more sensitivity, external coils and feedback can be used to produce sensors with resolution in the 100 mA/m or milli-oerstead range.

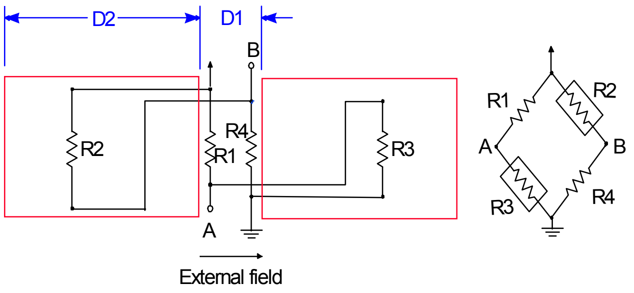

Figure 6. Configuration of GMR resistors in a Wheatstone bridge sensor. Flux concentrators are shown: D1 and D2 are the lengths of the gap between the flux concentrators and the length of one flux concentrator respectively.

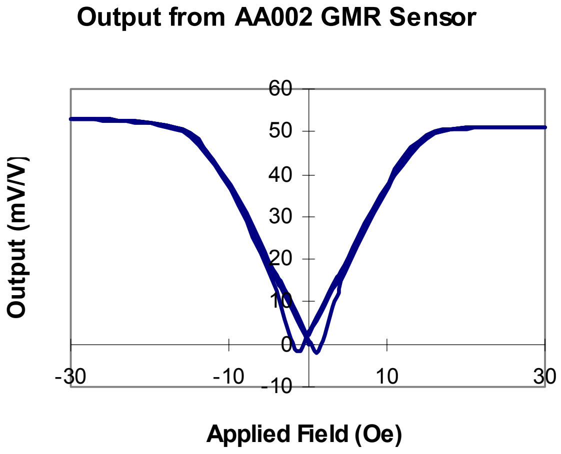

Figure 7. The output from a low-field GMR Wheatstone bridge sensor under bipolar excursions of applied field.

An example of the output from a low-field GMR bridge sensor is shown in Figure 7. The curve traces out a full bipolar excitation of the sensor. The bipolar hysteresis shown is only observed when the sensor crosses from a large negative excursion to a positive excursion or visa versa. The unipolar hysteresis is shown by the two lines on each side which almost coincide. This sensor has a bridge resistance of 5 kΩ and a slope sensitivity of 3.7 mV/V/Oe. The flux concentrators on this sensor provide a gain of approximately 16. The size of the sensor die is 0.44 by 3.37 mm and it is packaged in an 8-pin SIOC package with a footprint of 6 by 4.9 mm.

Wheatstone bridge sensors can also be made from STD materials. Because of the insulating layer, high resistances can be obtained in very small areas. These SDT sensors can be operated in a hysteretic or linear mode depending on the sensing application. With no current passed through the integrated biasing straps, the output has an open shape with considerable hysteresis. This mode is useful for on-off types of applications in which one wants a large signal change to occur at fields above a certain level, say ± 1 Oe. This type of output is shown as the dotted line in figure 8 below. The switching threshold for this curve can be adjusted by changing the length of the flux concentrators. With approximately 40 mA of current through the integrated biasing coil, the output becomes linear, with a lower slope and much less hysteresis. This mode is ideal for sensing very small changes in magnetic field. Sensor output using this mode of operation is shown as the solid line in figure 8.

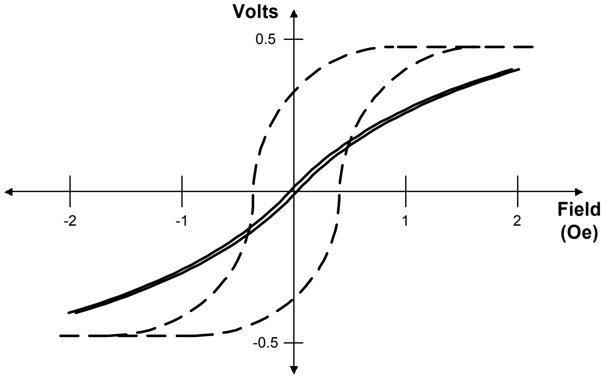

Figure 8. Bridge sensor output for a 12 kW bridge using 10 V bridge excitation. The dotted line is with no field biasing current while the solid line is with 40 mA.

These sensors are still under development. Table I shows the preliminary operating parameters of Wheatstone bridge STD sensors.

Table I. Preliminary operating parameters of STD sensors.

Sensor Type:	Wheatstone Bridge
Linear Field Range:	+/- 0.5 Oe
Output vs. Field polarity:	Bipolar
Voltage sensitivity:	~10 to 100 mV/V/Oe
High frequency noise floor:	~10 to 100 nOe/$\sqrt{\text{Hz}}$
Noise at 1 Hz:	~1 to 10 μOe/$\sqrt{\text{Hz}}$
Saturation Field	+/- 1.0 Oe
Bridge Resistance:	5 to 50 kΩ
Maximum bridge power:	2 to 20 mW
Flux Concentration:	10 x
Die Size:	1.65 x 2.14 mm
Operating temperature range:	-40 ^{0}C to +185 ^{0}C
Maximum operating voltage:	15V

A useful feature of sensors made with SDT material is the ability to fabricate a very wide range of resistance values using the same footprint. The 5 to 50 kΩ specifications above are towards the lower end of the resistance range. If a particular application requires a higher resistance value, resistances as high as 10 MΩ sensor are relatively easy and economical to fabricate.

CIRCUIT CONSIDERATIONS

The ultimate low-field limit on any magnetic sensing system is noise. If the signal to noise ratio is less than one, it is difficult to have a meaningful measurement. Fortunately, there are several methods of improving the signal to noise ratio if one understands the sources of the noise.[10] Noise can divided into two categories – inherent and transmitted. The sensor produces inherent noise and the sensing system while transmitted noise is coupled into the sensing system from the outside world. Inherent noise can include such things as sensor and amplifier offset, thermal noise, and 1/f noise. Transmitted noise includes magnetic fields from unwanted sources and electrical noise from external sources picked up by the sensing system.

Thermal noise is associated with random thermal motions at an atomic level. Since the noise is uniform with frequency, the noise voltage within a given bandwidth is proportional to the square roots of the resistance, temperature, and bandwidth. At room temperature the noise voltage divided by the square root of the bandwidth is $0.13 \sqrt{R}$ (nV/$\sqrt{\text{Hz}}$) or 9 nV/$\sqrt{\text{Hz}}$ for a 5 kΩ sensor. To minimize thermal noise, limit the bandwidth to the frequencies of the magnetic signal of interest and use small resistors. The resistance of the sensing resistor itself may be constrained by power and amplification considerations.

A second source of inherent noise in all conductors is ***1/f* noise**. This noise is due to due to point to point fluctuations of the current in the conductor.[11] It is proportional to the inverse of the frequency and often dominates below 100 Hz. Our best estimates for the *1/f* noise in a 5 kΩ multilayer GMR sensor is 300 nV/$\sqrt{\text{Hz}}$ at 1 Hz and 1 mA. At the lowest frequencies it is difficult to distinguish it from drift. While thermal noise is independent of current and exists even without current, *1/f* noise is proportional to the current and increases with increasing current. Bandwidth limitation, especially on the low frequency end will decrease *1/f* noise. As with any random noise source, averaging a repetitive signal will increase the signal to noise ratio by the square root of the number of singles averaged.

Transmitted noise sources include any voltages picked up by the circuit as well as any magnetic signals picked up by the sensor which are not part of the desired magnetic signal. Any time varying magnetic field will not only produce a signal in a magnetic sensor, it will also induce a voltage in any circuit loop proportional to the circuit loop area and the time rate of change of the magnetic field. To minimize this inductive pick up, good circuit practices must be followed including minimizing any potential circuit loops and placing amplification as close to the sensor as possible. Electrical currents generate magnetic fields. Therefore, there are usually stray 60 Hz magnetic fields in any industrial location. The increasing use of computers and other equipment with rectifiers-fed capacitor-input power supplies results in non-sinusoidal currents that produce harmonics of 60 Hz. Any moving or rotation magnetic material in equipment will produce a time varying magnetic field at frequencies characteristic of their period. The Earth's magnetic field itself, and its slow random variation is a source of noise if extremely low frequency magnetic fields are of interest. Transmitted magnetic noise sources are usually best minimized by filtering and if practical, using magnetic shielding. When measuring fields from a dipole source close to the sensor, a second sensor can be located at a distance at least twice as far from the dipole. The difference between the two signals, when adjusted for differences in sensitivity will be at least 7/8 the signal while canceling out the signals from remote sources.

Instrumentation amplifiers are a good choice for use with low-field Wheatstone bridge GMR sensors. When combined with an operational amplifier, gains of several thousand are easily achieved. High-pass and low-pass filters formed from passive components can be incorporated in the circuit to limit noise and to avoid saturation of the amplifiers by any offset or by any dc magnetic signal such as the Earth's field. Such a circuit is shown in figure 9. If 60 Hz noise is large enough to cause difficulties, a notch filter can be added. When using high gain with magnetic sensors, small effects such as the magnetization of electrical components can cause additional offsets. Most surface mount resistors have ferromagnetic nickel plating on their ends, and most battery casings are ferromagnetic. When in doubt, try picking up components with a permanent magnet.

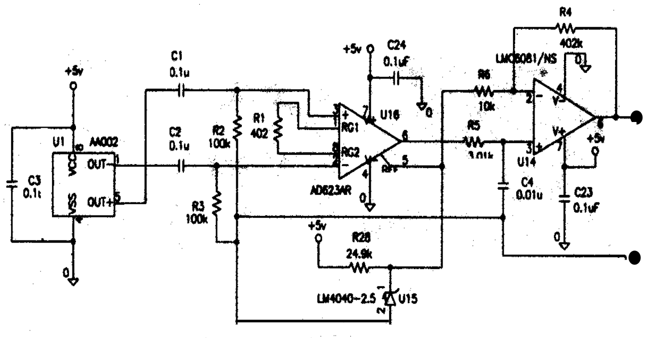

Figure 9. A low-field GMR Wheatstone Bridge sensor with instrumentation amplifier, operational amplifier, and high and low-pass filters.

When designing a magnetic sensor for searching for magnetic dipoles such as a permanent magnet or a buried surveying stake, it is difficult to differentiate the dc signal from the object sought from the dc signal from the Earth's magnetic field. The method described above of using two sensors in a differential mode can be used in this application. At its surface, the Earth's magnetic field is relatively uniform with a very small gradient due to the great distance from its source. The gradient of the magnetic field from a dipole meters to tens of meters away is much larger. Using miniaturized GMR sensors, a portable, **long-baseline gradient field sensor** can be constructed. . The directional sensitivity of GMR sensors increases the ease of locating the remote object as the sensor array is rotated and moved.

Magnetic biasing is often important in low-field sensing. Other than permanent magnets, most magnetic materials will not have a significant magnetization unless a permanent magnet or the magnetic field from a current in a coil has magnetized them. This limitation is especially true for small particles of magnetic materials. The art of biasing is to be able to magnetize the object to be detected so that it produces a magnetic field along the sensitive axis of the sensor while not saturating the sensor with the biasing field. The simplest method of biasing Is to pass the object to be magnetized over a permanent magnet and then transport it to the vicinity of the sensor. This method works well in such applications as currency detection and reading MICR numbers on checks. The articles to be read are being moved by a transport mechanism and passed over the magnetic sensor one at a time. A permanent magnet can be placed at some point upstream remote enough not to saturate the magnetic sensor. The bills or checks are prepared with their particles in a reproducible magnetic state. A second method of magnetic biasing is to make use of the fact that thin-film GMR sensors are relatively immune to fields perpendicular to their sensitive axis. A permanent magnet can be placed in close proximity to the GMR sensor with its magnetic axis perpendicular to the sensor's sensitive axis. With proper positioning the sensor will see little or no field. When a magnetizable object approaches the end of the sensor, there will be a component of the magnetic field along the sensitive axis as is shown in figure 10. This method of biasing is often called back biasing because the magnet is usually attached to the back of the sensor. By using two opposing pole permanent magnets one can double the desired component of magnet field at the object to be sensed while reducing the field at the sensor to near zero. A final reason for biasing the sensor is to move it away from the origin. If the sensor is operating at the field corresponding to either of the minima in figure 7, the slope gain of the sensor is near zero. If the field decreases, it can even operate on a segment of the curve with negative slope even though the field is positive. Biasing the sensor slightly up the curve avoids these problems. The biasing can be accomplished either by a small permanent magnet judiciously located or by a small current in a trace on the printed circuit under the sensor perpendicular to the sensitive axis. A single trace under the sensor will provide 1 mOe/mA; multiple turns will provide proportionately more.

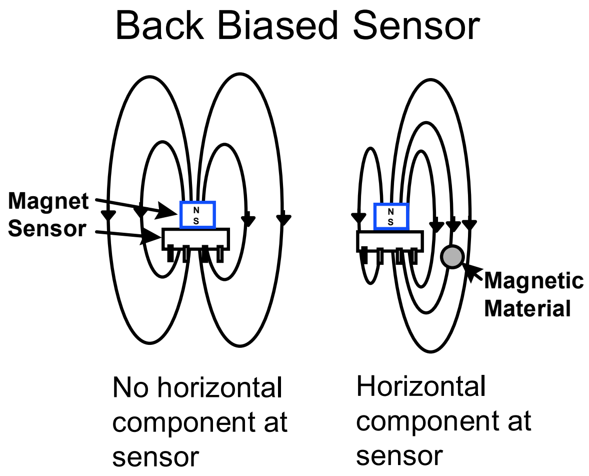

Figure 10. Back biasing of a magnetic sensor to detect magnetizable objects.

If the permanent magnet described above in back biasing is replaced with a coil, one can do **ac biasing** of the object to be detected. Using ac biasing non-ferromagnetic conducting objects can be detected. The method of using an ac magnetic field to detect a conductor is called eddy current sensing. The ac magnetic field induces currents in the conductor in a direction to oppose the applied field. If the coil is centered on the sensor with its axis perpendicular to the sensitive axis, the sensor will have minimal output unless a conductor, or defects in the conductor cause an asymmetry in the magnetic field and, therefore, a component of field along the sensitive axis of the magnetic field sensor. AC excitation also has application for ferromagnetic targets. By exciting the object or magnetic particles to be detected at some given frequency, the only signal of interest is at the excitation frequency. A narrow filtering range can reduce the noise by looking only at the signal at the excitation frequency.

Some low-field applications involve more than the magnetization at a single point or along a line as the sample passes the sensor. In these cases **arrays of detectors** can be assembled. Because of their small size and low power requirements GMR sensors are ideas for such applications. Although packaged GMR low-field sensors can only be placed on approximately 6 mm centers, bare GMR die can be mounted on ceramic substrates with less than 1 mm spacing and wire bonded to pads on the ceramic substrate. On-board electronics can sum up signals from several sensors to give a reading over wider path than afforded by a single sensor. For other applications multiple sensors can be strobed and the output multiplexed to minimize the number of connections to the sensor array. GMR sensors or sensor dice can be packaged along three orthogonal axes to give miniature 3-axis magnetic sensors.

APPLICATIONS

In applications such as **detection of motor vehicles**, the Earth field acts as a biasing magnet resulting in a magnetic signature from various parts of the automobile as it passes a sensor. The x, y, and z components of the signature can be detected by magnetic sensors buried in the road or even by the side of the road. Figure 11 shows the three components for a small automobile and a motorcycle. The x direction is the direction of travel and the z component is vertical. The presence of a stationary vehicle can be detected by a single sensor. Since the magnetic field from an automobile when measured at the surface of the road is similar in size to the Earth's magnetic field of about ½ guass (40 A/m), the sensor and its circuitry must be nulled for this effect once it is installed. Detection of stationary vehicles is important for traffic control at traffic lights as well as for monitoring available spaces in parking ramps and resetting parking meters. Magnetic sensors can also be used for moving traffic. One such application is the counting and classification of motor vehicles passing over portable or permanent sensors in the road. By using two sensors separated by a small distance, speed, and therefore, vehicle length can be calculated for traffic classification. Small, low-powered GMR sensors allow the sensors, electronics, memory, and battery to be packaged in a low-profile, protective, aluminum housing the size of your hand.[12] Similarly circuits with two sensors can be used to monitor presence and speed of trains approaching road crossings in order to lower the crossing gates at an appropriate time.

Eddy current detection methods are used not only in proximity sensors, but also in non-destructive evaluation (NDE) of conducting metals. Applying magnetic sensors to eddy current sensing is somewhat similar to back biasing a magnetic sensor. A coil applies an ac field to the material under test. The coil is oriented such that its field is not in the direction of the sensitive axis of the magnetic sensor and will not affect the sensor. Eddy currents generated by the applied ac field in a continuous conducting sheet below the sensor will create a mirror image of the field from the coil and will also not affect the magnetic sensor. The presence of an imperfection or crack in the conductor will change the symmetry of the eddy currents resulting in a component of the magnetic field along the sensitive axis of the magnetic sensor. Eddy currents shield the interior of the conducting material with the skin depth related to the conductivity and the frequency. Therefore, by changing the frequency differing depths of the material can be probed. GMR sensors with their wide frequency response from dc into the multi-megahertz range are well suited to this application. The small size of a GMR sensing element increases the resolution of defect location as the detector is scanned over the surface in two dimensions.[13] For one-dimensional scans, an array of detectors can be used. Figure 12 shows the configuration of the sensor and coil for eddy current detection.

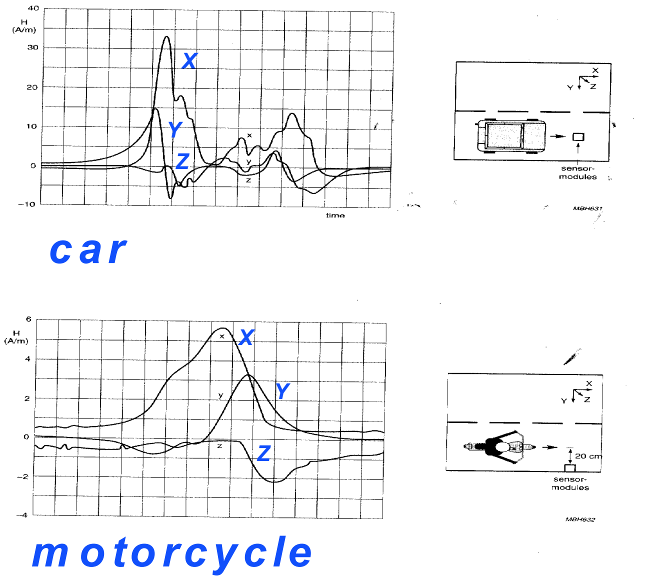

Figure 11. Magnetic signature from motor vehicles passing a 3-axis magnetic sensor. The maximum field for the car is 33 A/m (400 mG) and for the motorcycle 5.6 A/m (70 mG).

The **detection of magnetic ink** is a growing low-field magnetic sensor application. The use of iron oxide as a pigment in black ink has provided a method of reading and validating currency and other negotiable documents. The inclusion of magnetic particles in inks, while originally fortuitous, is now carefully controlled in some countries. Additional magnetic features are being added to currency as PCs and excellent quality color printers have moved counterfeiting from the realm of the skilled engraver to that of the high school student. One application is reading the Magnetic Ink Character Recognition or MICR characters on the bottom of checks. Figure 13 shows the magnetic signature of these characters. The magnetic sensor averages the signal over the entire height of the characters as they pass the magnetic sensor at a high rate of speed. The ink is magnetized in the plane of the paper by passing the checks over a permanent magnet upstream from the sensor location. The magnetized ink produces the magnetic signature that identifies each character as it passes the sensor. Each area produces a positive signal as it approaches and a negative one as it leaves. If the poles on the permanent magnet were reversed, the magnetic signatures would flip with positive excursions where there are now negative excursions and visa versa.

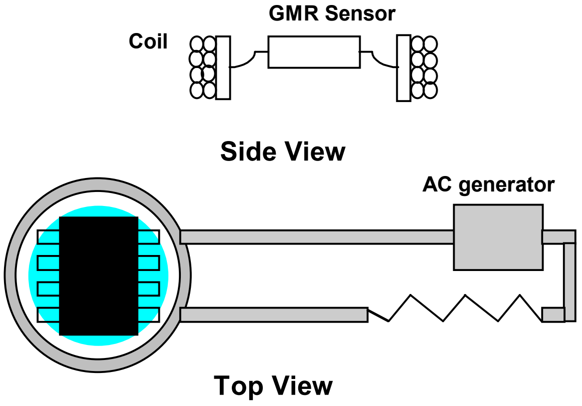

Figure 12. Arrangement of coil and GMR sensor for eddy current detection of defects in conductors.

The reading of currency is somewhat more difficult because the amount of magnetic ink is considerably less. The maximum field measured immediately above U. S. currency is less than 100 mOe or 8 A/m. Inductive read heads designed similarly to tape recorder heads need to be in direct contact to yield an adequate signal from U. S. currency. To avoid jamming in high-speed transport mechanisms it is desirable to be able to read the bill from up to 2 mm away. To achieve this goal, sensitive low-field sensors such as GMR sensors are utilized with amplification and filtering as discussed above in the section on instrumentation amplifiers. The small size of GMR sensors offers the possibility of making arrays of sensors to image a bill rather than just obtaining a signature along one line along or across the bill.

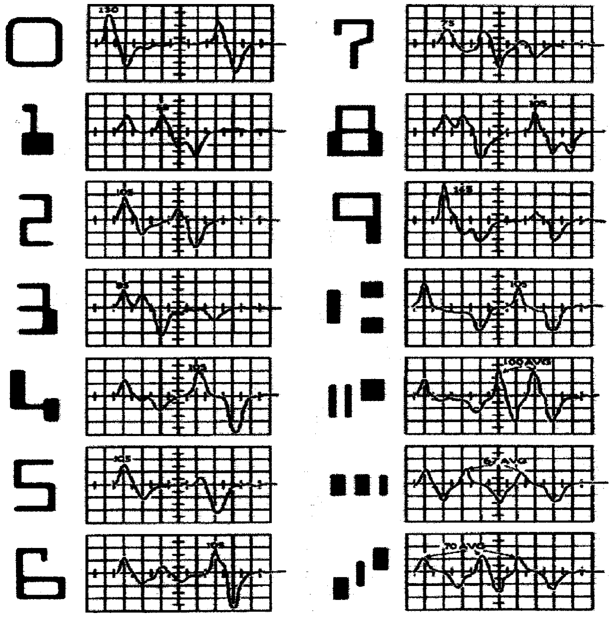

Figure 13, Magnetic signatures from Magnetic Ink Character Recognition (MICR) characters on the bottom of checks.[14]

Magnetic noise is common in the range of magnetic fields of interest to currency detection. Care must be taken to minimize moving magnetic materials in the transport mechanism. Current loops from adjacent electronics and fields from motors must be minimized. Shielding of the sensor takes some skill since the bills have to have a path by the sensor. Differential sensors with a second sensor 2 to three times as far away can also be used to minimize the effect of magnetic noise.

Geophysical surveying increasingly relies on sensors including magnetic sensors. Airborne surveys of magnetic anomalies are used to locate potential magnetic ore bodies. The magnetic fields of interest are considerably less than the Earth's magnetic field. Ground based magnetic surveys require portable equipment. Low-field GMR sensors are ideal for equipment packed into remote survey areas. As mentioned earlier, changes in conductivity of the soil due to water can be detected using eddy currents and magnetic sensors as can buried conducting pipes or even non-conducting pipes containing water. Eddy current detection is a non-contacting method that does not require placing electrodes in the ground, passing currents through the ground, and measuring potentials. The wide bandwidth of GMR sensors allow both time and frequency domain measurements to be made simultaneously. Arrays of sensors make 2-D and 3-D imaging possible. Liquid organic compounds have been shown to react with clays with varying response times to a given stimulus. Therefore, with a large bandwidth it may be possible to not only detect subsurface water flow but also determine organic contaminants.

Magnetic low-field GMR sensors are also of interest in locating other materials hidden in the soil – **unexploded ordnance** (UXO). Some ordnance can be located by its magnetic signature. For maximum sensitivity in the presence of the Earth's field, differential magnetic sensing is usually used. Differential magnetic sensing also avoids confusion of the desired signal with the changing component of the Earth's field along the sensors sensitive axis as the sensor is moved around to survey a region. Unfortunately, not all ordnance have ferromagnetic materials in them. Plastic cased land mines are designed to be difficult to locate and clear. For this type of UXO laboratories have been working with arrays of GMR sensors to look for magnetic anomalies in the background magnetism from the soil. The prevalence of iron oxide in soil provides a background magnetic signal. Where there is a hole or absence of magnetic signal is a potential location of UXO. Small, low-power GMR sensors are ideal for such an array of magnetic sensors.

The **sensing of body position** plays a role in various medical evaluations – the tracking of the movements of the eye or a limb for example. The position data can be correlated with other information such as electromyogram (EMG) readings to diagnose movement disorders. In some cases a small magnet can be attached to the body part to be monitored. For example, small magnets can been placed in scleral contact lenses. The position of the magnet can then be monitored by magnetic sensors mounted on an eyeglass frame. A 3-D measurement of motion of a limb including vertical inclination and horizontal azimuth has been accomplished using 3 orthogonal GMR sensors measuring vector components of the Earth's magnetic field together with 3 accelerometers.[7] The system was small enough so that it could be used in long-term ambulatory measurements of patients during normal activities. Three magnetic sensors are required because the Earth's field is a vector with horizontal and vertical components. By measuring all three components of the field, the orientation of the triaxial sensor relative to the fixed direction of the Earth's field could be calculated. The calculation is very similar to that for using magnetic sensors for compassing applications.[1] Care must be taken to bias the sensors onto a portion of their operating curve which will insure that rotating the sensor in the Earth's field will not result in passing a minimum in the response curve shown in figure 7.

A proof-of-concept **biosensor** experiment has shown the value of using GMR sensors with magnetic microbeads in a Bead ARray Counter (BARC).[8] An array of 80 x 5 μm GMR sensor elements was fabricated from sandwich GMR material. Each sensor was coated with different biological molecules that will bond to different materials to be assayed. The magnetic microbeads are also coated with the materials to be analyzed. The microbeads in suspension are allowed to settle onto the GMR sensor array where specific beads will bond to specific sensors only if the materials are designed to attract each other. Non-binding beads can be removed by a small magnetic field. The beads are then magnetized at 200 Hz by an ac electromagnet. The 1 μm microbeads are made up of nm sized iron oxide particles which have little or no magnetization in the absence of an applied field. A lock-in amplifier extracts the signal at twice the exciting frequency from a Wheatstone bridge constructed of two GMR sensor elements, one of which is used as a reference and two normal resistors. High-pass filters are used to eliminate offset and the necessity of balancing the two GMR sensor elements. With this detection system, the presence of as few as one microbead can be detected. The miniature nature of GMR sensor elements will allow an array to simultaneously test for multiple biological molecules of interest.

CONCLUSIONS

Solid State magnetic field sensors have revolutionized measurement and control in areas in which the magnetic fields, produced either by bias magnets or electric current, have been above that of Earth's field. These solid state devices have utilized both Hall-effect and AMR technologies. The silicon Hall-effect devices, however, have not been effective in working with fields much below 50 Oe. The advent of AMR and III-V Hall effect devices have been successful in working in near earth field applications but have had other drawbacks preventing wide spread utilization. GMR technology has also had some difficulty working in the < 0.5 Oe applications and/or micro-Oe variations. It has relied on significantly high amplification and/or biasing expertise to achieve the desired results.

The new GMR technology, spin-dependent tunneling (SDT) now promises to extend the low field solid state sensing horizon into areas previously dominated by significantly larger and power-hungry devices. This development mean that the array of products produced utilizing small fields or very small field changes will expand significantly and alter ways in which heretofore difficult measurements can be reliably made. These advances will take significant time and resources to perfect, but the gradual changes will soon become apparent in new products now under development. Magnetic sensing technology is moving forward into sensing smaller and smaller fields.

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