GMR and SDT Sensors and Arrays for Low-Field Magnetic Applications

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Abstract -- Because of their small size, low power, and relatively low cost, solid state sensors that detect magnetic fields lower than Earth's have found applications in all major industries. As these devices become more sensitive, they are being used to determine precise orientation and to detect natural and man-made geophysical anomalies, various physiological functions, metal defects, magnetic inks, and minute particles associated with immunoassay. New applications are being discovered daily as the current technology involves limitations due to size, weight, power consumption, and cost. As these applications develop, there is an emerging requirement to provide a matrix of low-field magnetic sensors for magnetic field images of the subject material or, as in the case of bioasssays, to handle multiple variables simultaneously. Application areas being investigated include currency detection (for reading the whole bill), eddy-current mapping for defect detection, geophysical anomalies, and bioassays. Matrices are currently being designed with several hundred magnetic pixels using both GMR (giant magnetoresistive) and SDT (spin dependent tunneling) materials. Several applications using these new magnetic arrays are presented.

INTRODUCTION

Sensing of magnetic fields is often utilized in industry for control and measurement.[1] In these industrial applications, relatively large magnetic fields are used to minimize the effect of background magnetic fields such as the Earth's magnetic field and fields from adjacent ferromagnetic objects. Despite the increased difficulties encountered with measuring 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 that measure magnetic fields or magnetic field gradients can detect small magnetic fields at considerable distances from soft magnetic materials magnetized by the Earth's magnetic fields. These objects include vehicles, buried surveying stakes, and lost wrenches. The black ink in many currencies and other negotiable documents contains small magnetic particles that act as dipoles. Currency validation including country and denomination can be based on the magnetic signature of a bill passed close to a magnetic sensor. Greater sensitivity allows larger bill-to-sensor gaps with less potential jamming of the bill path. Eddy current sensing to detect flaws in conducting materials or even differing conductivity in the soil requires high-frequency, low-field sensors. New concepts in bioassay require sensors that will detect the presence of micrometer-sized superparamagnetic particles.

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 graphical comparison in cost and power of several low field sensors all designed with the same minimum field resolution, 10^{8} Oe/√Hz, limited by thermal noise.

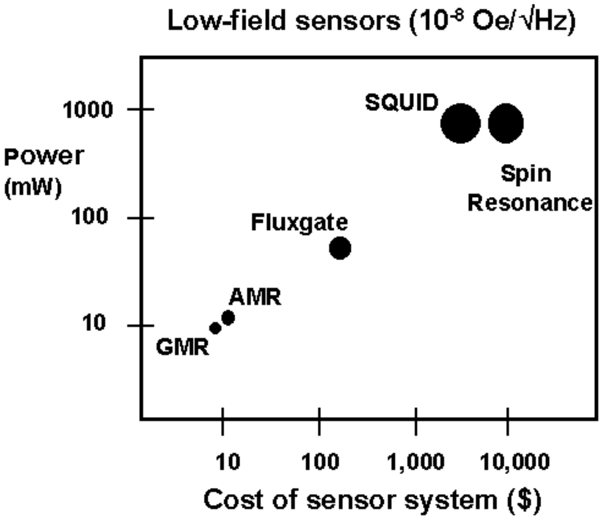

Figure 1. Comparison of low-field magnetic sensors designed with the same low field limit, 10^{8} Oe, using several magnetic sensor technologies. The size of circle indicates relative size.

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Increasingly, low-field applications require more information than the magnetization at a single point or along a single line as the sample passes the sensor. In these cases arrays of detectors must be used. Arrays can be used to build up an image of the magnetic fields in 1, 2, or 3 orthogonal directions over an extended area. An image can be generated by passing a linear array of sensors over the object to be imaged such as currency. In contrast, the information from a two dimensional array of sensors tens of cm on a side can be used to build an image of a buried object without moving the array.

GMR sensors are ideal for array applications because of their very small size and low power requirements. Although presently available packaged GMR low-field sensors can only be placed on approximately6 mm centers, bare GMR die can be mounted on substrates with less than 1 mm spacing and wire bonded to pads on the substrate. The multiple sensors can be sequentially addressed and the output multiplexed with on-board electronics 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. For extremely high spatial resolution arrays, GMR sensors with multiple sensing elements on each die can be fabricated. Sensing elements can be spaced with less than 10 µm on centers.

SDT/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 % and greater 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]

Spin dependent tunneling (SDT) structures are a recent addition to the materials exhibition GMR. In SDT structures an insulating layer separates two magnetic layers. Conduction is allowed by quantum tunneling through the insulator. The size of the tunneling current between the two magnetic layers is modulated by the angle between the magnetization vectors in the two layers. Figure 2 shows the layers and the structure of an SDT resistor manufactured using thin-film deposition and photolithography.

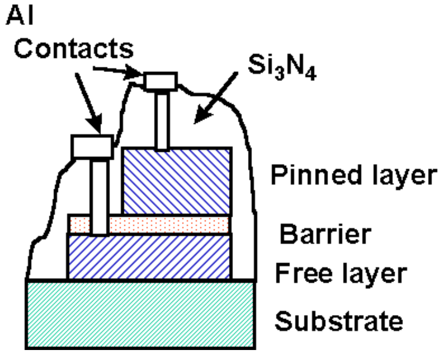

Figure 2. The layers and structure of an SDT resistor.

Changes of resistance with magnetic field of 10 to 40 % have been observed. The field required for maximum change in resistance depend upon the composition of the magnetic layers and the method of achieving antiparallel alignment. Values of saturation field range from 0.1 to 10 kA/m (1.25 to 125 Oe) offering at the low end, the possibility of extremely sensitive magnetic sensors. Figure 3 compares the output for various magnetoresistive sensors. Note the significantly larger sensitivity for the bipolar SDT sensor compared to the bipolar AMR sensor and the unipolar GMR sensors.

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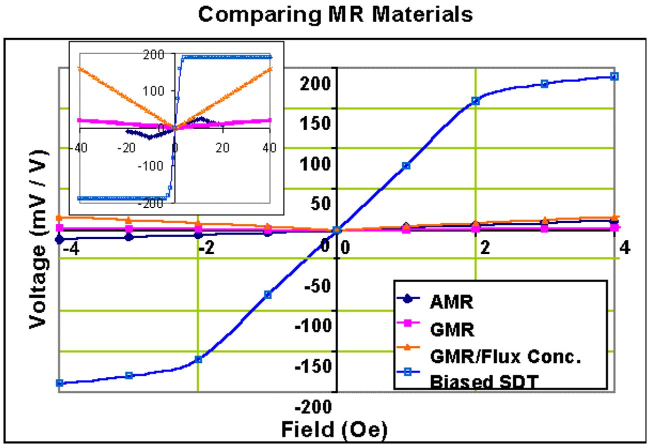


Figure 3. Comparison of sensors constructed from various magnetoresistive materials. The inset box shows response over a larger range of fields.

The insulating, tunneling layer provides inherently high resistance sensors suitable for battery operation. 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.

LOW 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 its maximum magnetization. As an example, a cylindrical ferromagnet whose diameter and length are one-half those of a larger cylindrical magnet 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 small magnetic sources 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. In both cases the smaller the field detected, the more useful the sensor. The field detected must also be separated from the Earth's magnetic field that 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 in 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 filtered out. When doing a search for a magnetic dipole that 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 the dipole field 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 underground anomalies including unexploded ordnance (UXO) using magnetic sensors and arrays of magnetic sensors.

Non-magnetic metals can be detected by using magnetic sensors and eddy currents. An ac magnetic field generated by a current in a coil causes eddy currents in the conducting material that 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 detect a magnetic field component caused by this change. This same general principle can be used for subsurface geophysical exploration.[5] 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 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 and even the country of origin 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 several mm from U. S. currency. As the distance to the bill increases, however, the minimum resolvable feature size also increases. 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 Medical applications that involve detecting small are electrical currents that 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 and integrating the motion starting from a known position, the actual position can be calculated.[6]

Rapid, portable biosensors that measure the presence of DNA or antibodies are a recent area of research using low-field magnetic sensors.[7,8] Small magnetic beads coated with biological molecules are allowed to settle on substrate with substance that 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. In the future suchbiosensors will be used for applications ranging from tailoring the treatment to the individual to detection of biological warfare agents in the field.[9]

SDT SENSORS

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.[10] This material exhibits a phenomenon called Spin Dependent Tunneling (SDT) that results in a significant change in effective resistance due to a change in the applied field. (See figure 2.) 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 that presently require fluxgate magnetometers. As with other NVE GMR sensors they are very small (SOIC-8 package), require little power, and are easily combined with other electronics.

The magnetization of one ferromagnetic layer of the SDT sandwich is fixed or pinned by being coupled to an adjacent layer of antiferromagnetic material. The direction of the other ferromagnetic layer is controlled by the applied magnetic field. When the direction of magnetization is parallel to the fixed layer, the resistance is minimum. When it is anti-parallel, the resistance is maximum. Therefore, an SDT resistor has a bipolar response to magnetic fields. As with other GMR materials, Wheatstone bridge sensors can be fabricated from SDT materials. Two of the SDT resistors in the bridge are shielded from the applied magnetic field. The other two resistors can be placed between flux concentrators to increase the sensitivity of the sensor. The output of such a SDT Wheatstone bridge is shown in figure 4. The dotted line shows the natural bipolar output of the bridge. Very little field is required to rotate the free layer into either their parallel or anti-parallel orientation; however, there is considerable hysteresis. Adding a biasing field perpendicular to the direction of the pinned layer can largely eliminate this hysteresis. With zero applied field the free layer is perpendicular to the pinned layer. Fields in the direction of the free layer magnetization decrease the resistance. Fields in the opposite direction increase the resistance. The behavior of a sensor with an orthogonal biasing field is shown as the solid curve in figure 4.

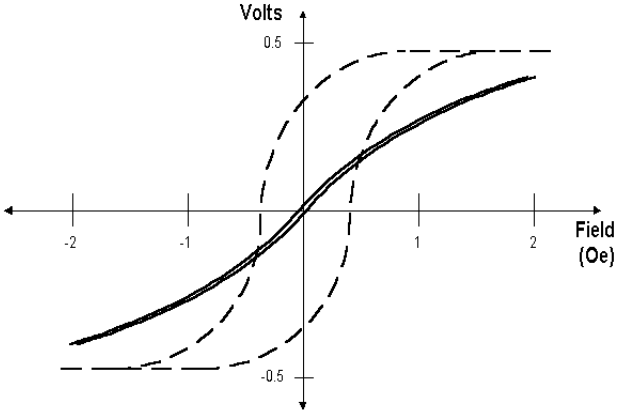


Figure 4. Bridge sensor output for a 12 kΩ bridge using 10 V bridge excitation. The dotted line is with no field biasing current while the solid line is with 40 mA current.

Orthogonal biasing fields can be provided by fabricating on-board coils on the sensor chip over the SDT material. Additional on-board coils can provide fields parallel to the sensitive axis for use in feedback circuits. The schematic of an SDT bridge sensor with on-board biasing and feedback coils in an 8-pin SOIC package is shown in figure 5.

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 12 kΩ bridge resistance in figure 4 is near the lower end of the achievable resistance range. If a particular application requires a higher resistance value, resistance as high as 10 MΩ are easy and economical to fabricate.

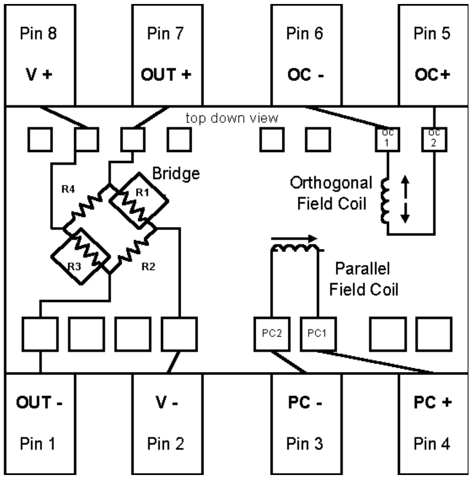
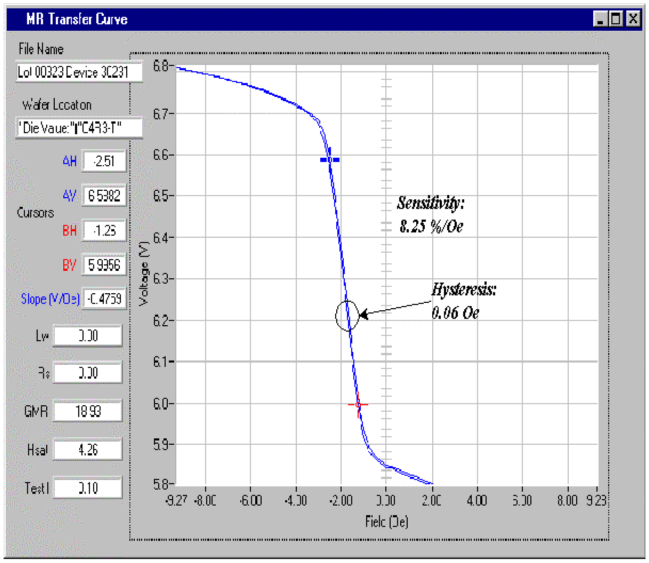


Figure 5. Connections for a SDT bridge sensor with on-board biasing and feedback coils packaged in an 8-pin SOIC package.

Research continues on increasing sensitivity and decreasing hysteresis. The output from a bridge sensor made from a newly developed SDT material is shown in figure 6. The sensitivity is 8.25 %/Oe and the hysteresis is 0.06 Oe. Although there is an offset in both output and field, future sensors and their associated electronics will reduce these offsets.



File Name: Lot 00323 Device 3C231

Wafer Location: 'Die Value:"1"C4R3-T"

AH: -2.51

AV: 6.5382

BH: -1.23

BV: 5.9356

Slope (V/Oe): -0.4759

Lw: 0.00

Rs: 0.00

GMR: 18.93

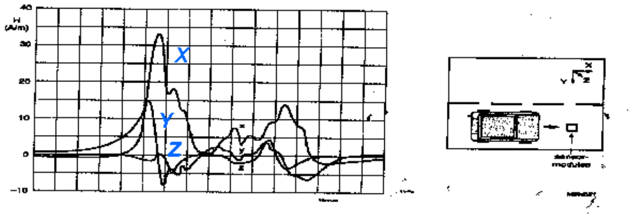
Hsat: 4.26

Test I: 0.10

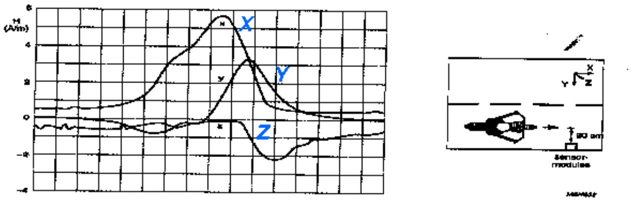
Figure 6. Output from an SDT bridge sensor using orthogonal field biasing. The sensitivity is 8.25 %/Oe or an output of over 80 mV/V/Oe.

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 magnetic signature can be detected by magnetic sensors buried in the road or even by the side of the road. Figure 7 shows the three field 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 Oe (40 A/m), the sensor and its circuitry must be nulled for the Earth's field 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 a two-sensor array with the sensors separated by a small distance, speed and signal duration can be measured and the 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 a hand.[11] Similarly arrays 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.



car



motorcycle

Figure 7. Magnetic signature from motor vehicles. The maximum field for the car is 33 A/m (400 mOe) and for the motorcycle 5.6 A/m (70mOe).

Eddy current detection methods are used not only in proximity sensors, but also in non-destructive evaluation (NDE) of conducting metals. 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, therefore, will not saturate 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 changes 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 raster scanned over the surface.[12] More rapid scans can be performed using an array of detectors. Figure 8 shows the relative positions of the sensor and coil for eddy current detection.

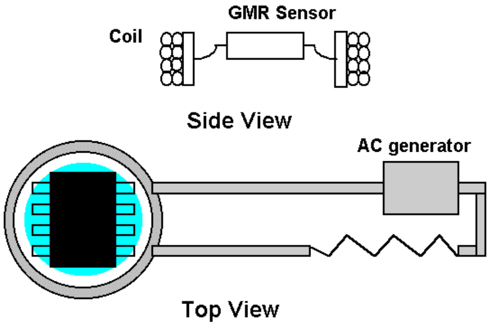


Figure 8. Arrangement of coil and GMR sensor for eddy current detection of defects in conductors.

A prototype of a GMR based eddy current probe has been built and successfully tested for detecting cracks of calibrated width and depth.[13] Figure 9 shows the output of such a probe. The asymmetry in the magnetic field is detected on either side of the crack. Additionally, it has been demonstrated that the unidirectional sensitivity of GMR sensors enable the detection of cracks at, and perpendicular to, the edge of a specimen. This discrimination is possible because the sensitive axis of the GMR sensor can be rotated to be parallel to the edge. Consequently, the signal is due only to the crack. With inductive probes, the edge will produce a large signal that can mask the signal produced by a crack. This capability represents a very simple solution to a difficult problem encountered in the aircraft industry (detecting cracks that initiate at the edge of turbine disks or near the rivets.

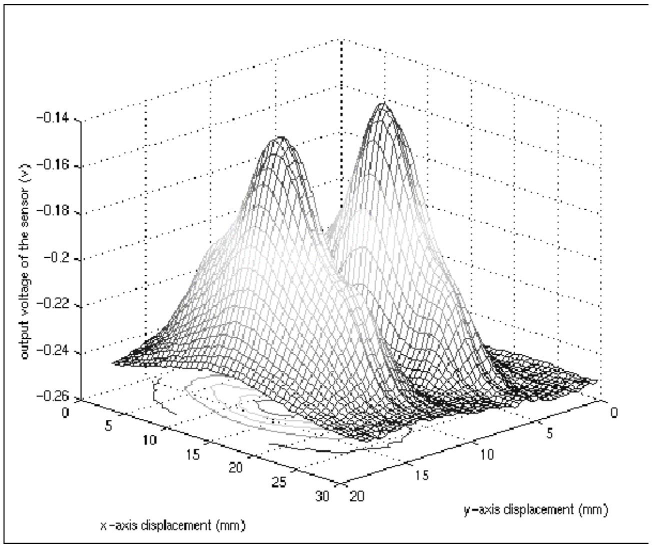


Figure 9. Output of GMR eddy current sensor when scanning a subsurface crack. Crack is 15 mm long and placed 1 mm below the surface of an aluminum specimen.[13] (Courtesy of UNC-Charlotte)

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. 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 such application is reading the Magnetic Ink Character Recognition or MICR characters on the bottom of checks. 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 a few mm away. To achieve this goal, sensitive low-field sensors such as GMR sensors are utilized with amplification and filtering. The small size of GMR sensors offers the possibility of making closely spaced arrays of sensors to image a bill rather than just obtaining a signature on one line along or across the bill.

Magnetic noise is common in the range of magnetic fields of interest to currency detection. Care must be taken to minimize the presence of moving magnetic materials in the transport mechanism. Fields from adjacent electronics and motors must be reduced. Differential sensors with a second sensor 2 to three times further from the bill 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. The wide bandwidth of GMR sensors allow both time and frequency domain measurements to be made simultaneously. Arrays of sensors make simultaneous 2-D imaging possible. Liquid organic compounds have been shown to react with clays with varying response times to a stimulus.[5] 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). For maximum sensitivity in the presence of the Earth's field, differential magnetic sensing is conventionally used. Differential magnetic sensing 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.[6] 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 tri-axial 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 applicaitons.[1]

Although magnetic sensing has been applied to **biological diagnostics** in the past, the sensors used, such as SQUIDs (superconducting quantum interference detectors), have limited the deployment of such systems to the field due to their size and power constraints. Solid state magnetic sensors now promise to change this picture by facilitation miniaturized magnetic sensor based systems. The applications include detection of the small magnetic fields created by nerve impulses for monitoring the activity of the heart and brain. The previously insurmountable barrier to the use of solid state magnetic sensors, sensitivity, is being overcome by sensors utilizing GMR and SDT materials. These highly sensitive near-micrometer sized sensing elements stand at the edge of biological diagnostics research.[14]

Magnetic particles have been used for many years in **biological assays**. These particles range in size from few nanometers up to a few microns, and in composition from pure ferrite to small percentages of ferrite encapsulated in plastic or ceramic spheres. The beads are coated with a chemical or biological species such as DNA or antibodies that selectively binds to the target analyte. To date, these types of particles have been used primarily to separate and concentrate analytes for off-line detection.

The selectivity of sample and target can be used as a rapid sensitive detection strategy with the on-line integration of a magnetic detector. This integration is facilitated by the development of solid-state GMR sensors as the magnetic detectors in this application.

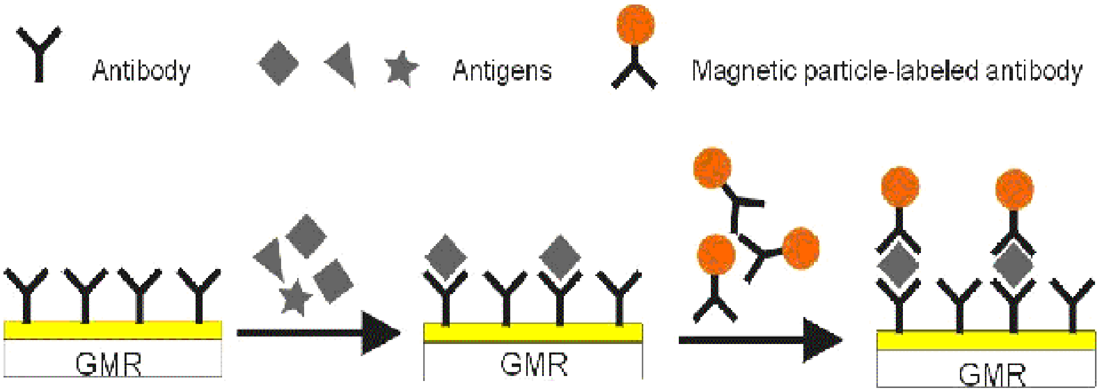


Figure 10. Antigens are detected by flowing them over a sensor coated with antibodies to which they bind. The magnetic particle-labeled antibodies then bind to the antigens providing a magnetic indication of the presence of those antigens.

These sensors have the unique advantage of being compatible with silicon integrated circuit fabrication technology resulting in a single detector, or even multiple detectors, that can be made on a single chip along with any of the required electrical circuitry. Results from theoretical modeling, as well as laboratory results, show that GMR detectors can resolve single micrometer-sized magnetic beads.

In one demonstration system small magnetic beads, coated with a material that binds to the biological molecules to be analyzed are allowed to settle on a substrate that is selectively coated in different areas with substances that bond to specific molecules of interest. After removing the beads that are not bonded to the substrate via a molecule of interest, the presence of the remaining magnetic microbeads is detected by magnetic sensors in the array.[8] Figure 10 schematically shows the bonding of the beads to the sites via the molecules to be detected. 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.

Several groups have experimented with using commercially available GMR sensors to detect coated magnetic beads as biosensors. However, the performance of packaged sensors of any type is limited by the plastic encapsulation used to protect the underlying sensor chip. The 8-pin SIOC package used by NVE for commercial GMR sensors has a spacing between the GMR element and the top of the package of 0.5 mm and an even greater distance from the element to the end of the package. Magnetic microbeads when magnetized by an external field have a magnetic dipole field. This field is proportional to the volume of magnetic material and inversely proportional to the distance cubed. Detecting these small fields is increasingly difficult as the distance from the bead to the sensor increases. The rapid decrease in field with distance requires that the sensitive area be of similar size to the microbeads. If the sensitive area is much larger than the bead, only the portion of the magnetoresistive material close to the bead will be affected. Therefore the fractional change in resistance, and hence the sensitivity, will be maximized by matching the size of the sensor to the size of the bead. This requirement matches the attributes of SDT sensors.

There are several variations of the relative orientation of the beads, GMR detectors, and excitation fields. An important variation of the excitation field geometry is to apply a field normal to the plane of the GMR sensor. The thin-film GMR sensoris about 1000 times harder to magnetize in the direction normal to its sensitive axis, so a much larger magnetizing field can be applied to the beads without saturating the GMR sensors.

In a proof of concept experiment an array of 80 x5 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 were coated with the materials to be analyzed. The microbeads in suspension were allowed to settle onto the GMR sensor array where specific beads bonded to specific sensors only if the materials were designed to attract each other. Non-binding beads were removed by a small magnetic field. The beads were then magnetized at 200 Hz by an ac electromagnet. The 1 µm microbeads were made up of nm sized iron oxide particles that have little or no magnetization in the absence of an applied field. A lock-in amplifier extracted the signal that occurred at twice the exciting frequency from a Wheatstone bridge constructed of two GMR sensor elements, one of which was used as a reference and two normal resistors. High-pass filters were 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 could be detected. The miniature nature of GMR sensor elements allows an array to simultaneously test for multiple biological molecules of interest as is shown in Figure 11.

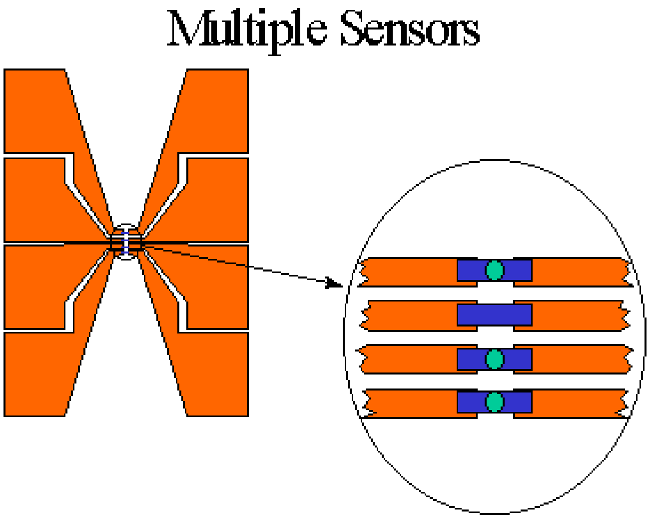


Figure 11. In a multiple sensor array each location is coated to bond to a different antigen. This schematic diagram shows beads on three of the four locations.

An integrated GMR sensor can include the sensors, the processing electronics, and even the current straps that provide the field to magnetize the microbeads on the same substrate. Figure 12 shows a cross section of such a sensor. The next challenge will be to combine the integrated sensors with fluid handling systems so that compact systems can be built to automatically analyze biological materials in the field without extensive laboratory equipment.

CONCLUSIONS

Solid State magnetic field sensors have been commercially available for over 25 years. In that period they have revolutionized measurement and control. These sensors worked in areas in which the magnetic fields, produced either by bias magnets or electric current, have been above that of Earth's field. 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.

GMR and SDT Sensors and Arrays for Low-Field Magnetic Applications

Carl H. Smith and Robert W. Schneider

The new GMR technology, spin-dependent tunneling (SDT) is now extending the low field solid state sensing horizon into areas previously dominated by significantly larger, non-solid state and power-hungry devices. As with the introduction of the first solid state devices, these new devices will alter the ways in which we deal with many of today's measurement and control problems. The development of these very small sensors, measuring very small magnetic field changes, are certainly well within the bounds of the much publicized "National Nanotechnology Initiative".

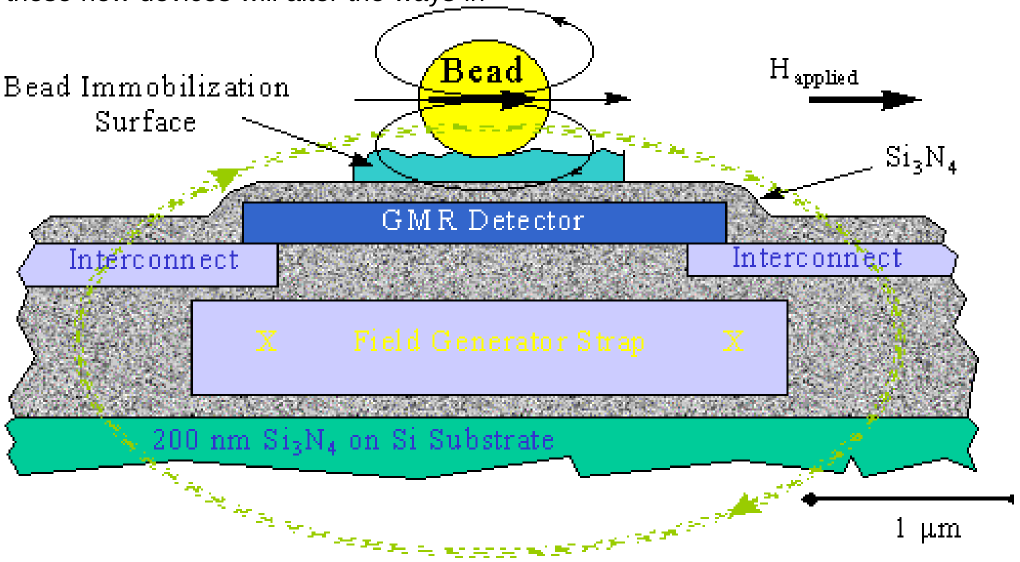


Figure 12. In an integrated GMR sensor the field that magnetizes the immobilized bead can be generated by a strap located in the sensor itself. The chip can also include the processing electronics.

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REFERENCES

[1] Michael J. Caruso, Tamara Bratland, C. H. Smith, and Robert Schneider, "A New Perspective on Magnetic Field Sensing," *Sensors Magazine*, vol. 15, no. 12, (December 1998), pp. 34-46.

[2] Carl H. Smith and Robert W. Schneider, "Expanding The Horizons Of Magnetic Sensing: GMR," *Proceedings Sensors Expo Boston*, pp. 139-144 (Helmers, Peterborough, NH, 1997).

[3] J. Daughton, and Y. Chen, "GMR Materials for Low Field Applications," *IEEE Trans. Magn.*, vol. 29, 2705-2710 (1993).

[4] J. Daughton, J. Brown, R. Beech, A. Pohm, and W. Kude, "Magnetic Field Sensors Using GMR Multilayer," *IEEE Trans. Magn.*, vol. 30, 4608-4610 (1994).

[5] T. D. McGlone, "Exploration and Detection of Subsurface Water Using Broadband Electromagnetic Sensors," *Environmental Geosciences*, vol. 5, no.4, 187-195 (1998).

[6] B. Kemp, A. J. M. W. Janssen, and R. van der Kamp, "Body position can be monitored in 3D using miniature accelerometers and earth-magnetic field sensors," *Electroencephalography and Neorophysi-ology*, vol. 109, 484-488 (1998).

[7] Carl H. Smith, Robert W. Schneider, and Mark Tondra, "Biosensors: a New Use for Solid-State Magnetic Sensors," *Sensors Magazine*, vol. 16, no. 12, (December 1999), pp. 14-20.

[8] D. R. Baselt, G. U. Lee, M. Natesan, S. W. Metzger, Paul E. Sheehan, and R. J. Colton, "A biosensor based on magneotoresistance technology," *Biosensors & Bioelectronics*, vol 13, 731-739 (1998).

[9] R.L. Edelstein, C.R. Tamanaha, P.E. Sheehan, M.M. Miller, D.R. Baselt, L.J. Whitman, and R.J. Colton, "The BARC Biosensor Applied to the Detection of Biological Warfare Agents," *Biosensors & Bioelectronics*, vol 14, 805 (2000).

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[10] Mark Tondra, A. Fink, R.S. Beech, D. Wang, J.A. Taylor, J.M Daughton, "Picotesla Field Sensor Design using Spin Dependent Tunneling Devices," J. Appl. Phys. 83, 6698 (1998).

[11] "Tiny Sensor Measures Vehicles Speed," nu-metrics News Release, 1998. <www.nu-metrics.com>

[12] T. Dogaru and S. T. Smith, "A GMR based eddy current sensor," (to be published in *IEEE Trans. Magn.*).

[13] Dogaru and S. T. Smith, "Detection of cracks near sharp edges by using giant magnetoresistance-based eddy current probe", accepted at SPIE's 5th Annual International Symposium on Nondestructive Evaluation and Health Monitoring of Aging Infrastructure, March 2000, to be published in *SPIE Proceedings*

[14] M. Tondra, M. Porter, and R. Lipert, "Detection of immobilized Superparamagnetic Nanosphere Assay Labels using Giant Magnetoresistive Sensors," American Vacuum Society Conf., Seattle, WA, October 25, 1999, (to be published in *J. Vac. Sci. & Tech.*)