Presented at Sensors EXPO Chicago June 3, 2003

VERY DENSE MAGNETIC SENSOR ARRAYS FOR PRECISION MEASUREMENT AND DETECTION

Dr. Carl H. Smith and Robert W. Schneider
NVE Corporation, Eden Prairie, MN

Abstract – Very dense arrays of micron-sized magnetic sensors combined with micron sensor spacing on a single chip can detect very small magnetic fields with high spatial resolution. These changes in magnetic fields are in the milligauss range, approximately 500 times less than Earth's field, and are required for magnetic biosensors, non-destructive test/inspection/evaluation, precision position measurement, document validation and magnetic imaging applications. By using a silicon substrate for the sensor elements, the signal conditioning and logic capability of integrated circuits can be utilized to reduce size, weight and power while optimizing system performance when compared to a collection of sensors supplying raw signals to a processor. This integrated technique, also, reduces the effect of noise and greatly simplifies the sensor/signal-processing interface. Applications of these very dense and sensitive micro-arrays will be discussed during the presentation including its possible implications for Homeland Security.

Introduction

Nano-technology arrays of micron-sized magnetic sensors and sensor spacing on a single chip can be used to detect very small magnetic fields with very high spatial resolution. Previously, solid-state magnetic sensors such as Hall-effect and Anisotropic Magnetoresisitive (AMR) sensors were not able to be applied in these applications either due to size, power or sensitivity issues. With the advent of the more sensitive Giant Magnetoresistive (GMR) and Spin-Dependent Tunneling (SDT) sensors, it has become possible to manufacture such arrays. These devices can be used to measure very small magnetic fields, or changes in magnetic fields, associated with magnetic biosensors, non-destructive test/inspection/evaluation, position, document validation including currency and credit cards, and magnetic imaging. Arrays of sensors are necessary for these applications either to provide a large number of independent, analytical sites in a small area as in biosensors or to allow high spatial resolution as in magnetic imaging. By fabricating sensors directly on a silicon substrate, the signal conditioning and logic capability of integrated circuits can be used to optimize system performance when compared to a collection of sensors supplying raw signals to a processor. This integrated technique reduces the effect of noise and simplifies the sensor/signal-processing interface. Several of these applications are becoming increasingly important for Homeland Security. Both the technology of GMR and SDT sensors and applications of these micro-arrays will be discussed during the presentation.

GMR Sensors Principles

The fundamentals of GMR and SDT materials have been covered in previous papers.[1 2] We will only briefly cover the basics here. The large changes in resistance with magnetic field are associated with a change in magnetic scattering of the conduction electrons at interfaces between the layers in these structures. If adjacent magnetic layers are magnetized in the same direction there is little magnetic scattering; if adjacent magnetic layers are magnetized in opposite directions, there is maximum magnetic scattering.

Sputter deposited multilayers of magnetic and non-magnetic metals can achieve large values of GMR (change in resistance divided by the minimum resistance). If these layers are the proper thickness, a few nanometers, the magnetic layers will couple anti-ferromagnetically. These multilayer GMR materials achieve maximum resistance in zero field and decreased resistance in applied fields. To achieve a change in resistance of 10 to 20 %, several repetitions of the magnetic and non-magnetic layers are used providing multiple interfaces for magnetic scattering to occur. Although the current flows predominantly in the plane of the thin film, the conduction electrons encounter the interfaces a sufficient number of times for the magnetic scattering to be noticeable

There are presently several GMR multilayer materials used in sensors and sensor arrays. The most commonly used material in commercial GMR sensors has a saturation field of 300 Oe and GMR of 15%. Newer FeCo/Cu multilayer materials with saturation fields below 100 Oe and GMR over 10 % are also used.[3] Figure 1 shows MR response of various multilayer materials. The slopes of the GMR curves in Figure 1 are 0.04 %/G for a conventional multilayer, 0.07 %/G for a low hysteresis multilayer, and 0.2 %/G for a high sensitivity multilayer material. In half bridge sensor configurations, these values correspond to outputs of 0.2, 0.35, and 1.0 mV/V/G (20, 25, and 100 nV/nT @ 10 V). The use of on-chip flux concentrators can increase these sensitivities.[1]

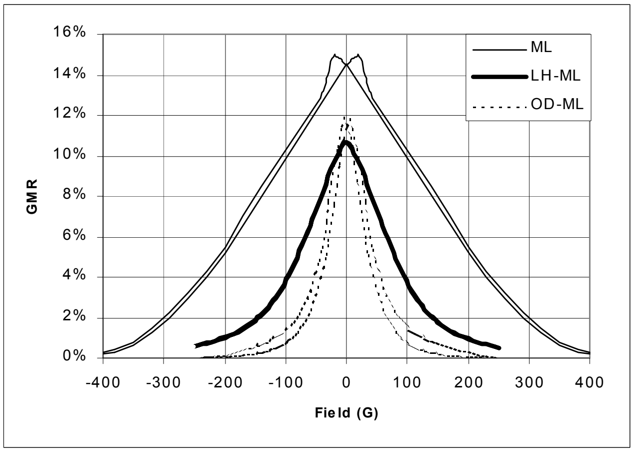


Figure 1.. Traces of GMR vs. field for conventional multilayer ML, low hysteresis multilayer LH-ML, and high sensitivity multilayer OD-ML materials.

Spin dependent tunneling (SDT) structures are a recent addition to materials exhibiting a large change in resistance with magnetic feld. In contrast to GMR structures, SDT structures utilize a thin insulating layer to separate two magnetic layers. The conduction between the conducting magnetic layers is by quantum tunneling. The size of the tunneling current between the two magnetic layers is affected by the angle between the magnetization vectors in the two layers. Changes of resistance with magnetic field of 10 to >60 % have been observed in SDT structures. The field required for maximum change in resistance depends 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. Prototype sensors with a 1.5 nm Al_2O_3 barrier thickness have demonstrated up to 40 % GMR and sensitivities of 30 mV/V/G (3 µV/nT @ 10 V).[4]

A diagram of the layers in a pair of low-power shape-biased SDT junctions is shown in Figure 2. Junctions in sensors are usually designed in series connected pairs so that contact can be made to the top layer of the junction by subsequent metal layers. The magnetization in the lowest CoFe layer is pinned as part of a multilayer structure consisting of a CrPtMn antiferromagnetic and the antiferromagnetically coupled CoFe/Ru/CoFe sandwich. The NiFeCo free layer on the bottom responds to the applied field. The shape factor biases the free layer along its long dimension eliminating the necessity of orthogonal field coils. The measured field is applied parallel to the axis of the antiferromagnetic structure. Depending upon the direction of the field, the resistance increases as the moments become more anti-parallel or decreases as they become more parallel. The response of an SDT magnetoresistor is shown in Figure 3.

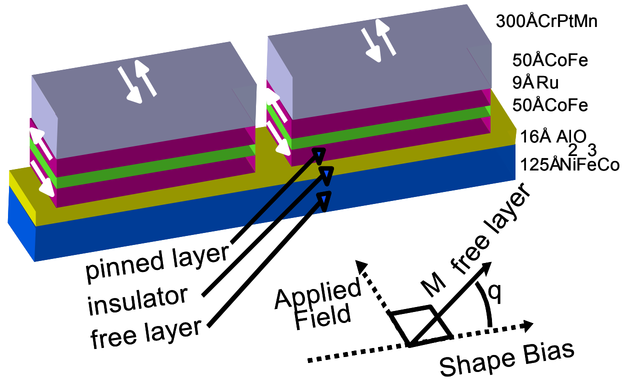
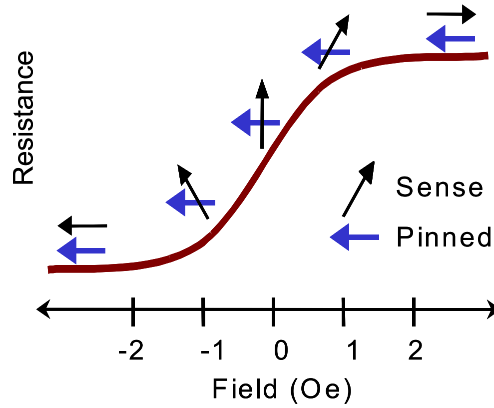


Figure 2. The layers and structure of a pair of SDT junctions. The magnetization in the lowest CoFe layer is pinned as part of the structure consisting of a CrPtMn antiferromagnetic and the antiferromagnetically coupled CoFe/Ru/CoFe sandwich. The NiFeCo free layer on the bottom responds to the applied field. The shape factor biases the free layer along its long dimension.

Figure 3. Resistance of a SDT junction as a function of applied field. The relative directions of the pinned and



sense or free layers are shown.

Sensor Arrays

The design of sensor arrays depends upon the specific application. Arrays used for imaging require many small elements along an extended, usually one dimensional, line in order to resolve small features.[5] In addition some provision must be made so that the sensing elements can achieve a close approach to the media to be imaged. Biosensors, on the other hand, use two-dimensional arrays of sensor spots to provide a large number of differing analytical sites in a small area.[6] The material to be analyzed is usually flowed over the sensor area. Imaging arrays that cover a significant width require extremely small sensing elements that operate at low power levels. For different applications GMR elements can be patterned to form simple resistors, half bridges, Wheatstone bridges, and even X-Y sensors. Single resistor elements are the smallest devices and require the fewest components, but they have poor temperature compensation and usually require the formation of some type of bridge by using external components. Alternatively they can be connected in series with one differential amplifier per sensor resistor. Half bridges take up more area on a chip but offer temperature compensation, as both resistors are at the same temperature. Half bridges can be used as field gradient sensors if one of the resistors is some distance from the other. They can function as field sensors if one of the resistors is shielded from the applied field.

Figure 4 shows a portion of an array of 16 GMR half-bridge elements with 5 µm spacing. The elements are 1.5 µm wide by 6 µm high with a similar size element above the center tap. The bottoms of the stripes are connected to a common ground connection and the tops of the half bridges are connected to a current supply. The center taps are connected to 16 separate pads on the die. A bias strap passes over the lower elements to provide a magnetic field to bias the elements.

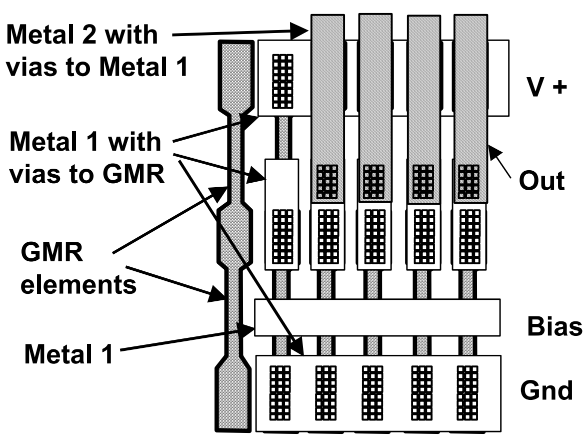


Figure 4. Part of a 16-element array of GMR half-bridge sensors with 5 µm spacing. The first three elements have portions removed to show the three layers and their interconnections.

Wider spacing between the elements can be achieved while retaining the directional sensitivity of narrow stripes by using serpentine resistors as the lower elements. Figure 5 shows the layout for a wider 16-element array with 15 µm spacing. Serpentine resistors with 4 stripes are used for the lower sensor element, and a single, longer stripe for the upper element. For clarity of the interconnections between layers, some of the elements are shown without metal 1 and metal 2 layers.

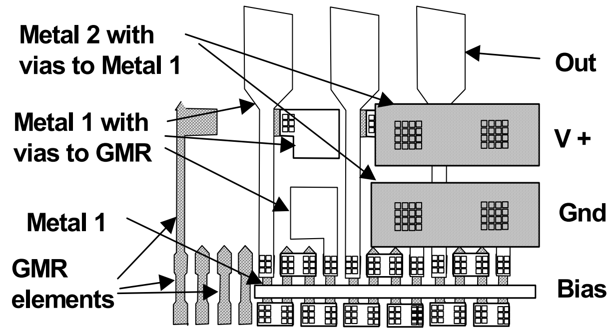


Figure 5. Four individual elements of a 16-element array of GMR half-bridge sensors with 15 µm spacing. The first elements are shown without metal 1 and metal 2 layers and without metal 1 layers for clarity.

An example of a biosensor array is shown in Figure 6. This biosensor has twenty individual sensor elements in a 4x5 matrix. The resistance of each element can be individually measured.

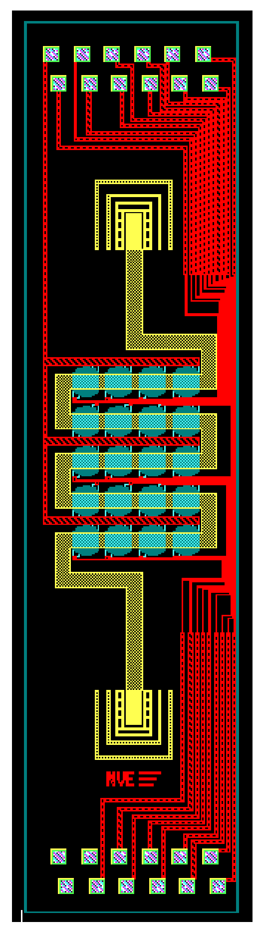


Figure 6. A biosensor array of 20 GMR elements arranged in a 4x5 matrix.

Sensor Underlayers

GMR and SDT materials are usually deposited on SiN insulating coatings over Si wafers. GMR materials have also been successfully integrated with both BiCMOS and bipolar semiconductor underlayers. This integration has been demonstrated in both integrated sensors and in magnetic couplers or isolators. A major obstacle that needed to be overcome was the planarization of the electronics underlayer to obtain the necessary "smoothness" for successful sensor depositions. Figure 7, an Atomic Force Microscopy (AFM) image of the electronics underlayer, shows the roughness of the substrate before the planarization required for integrated sensor array deposition.

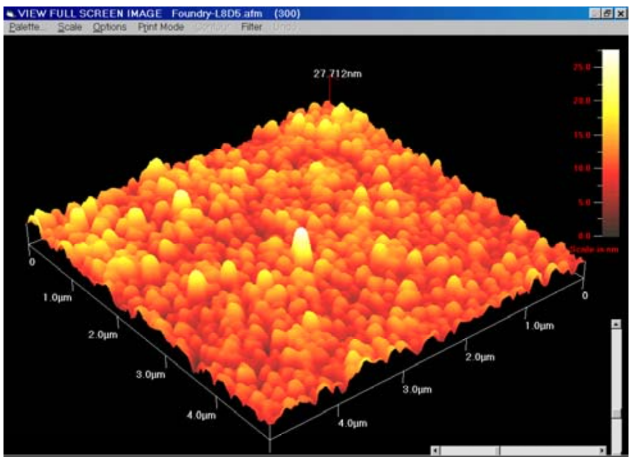


Figure 7. Atomic force Microscope (AFM) image showing the surface roughness of a substrate before planarization. RMS roughness 2.9 nm.

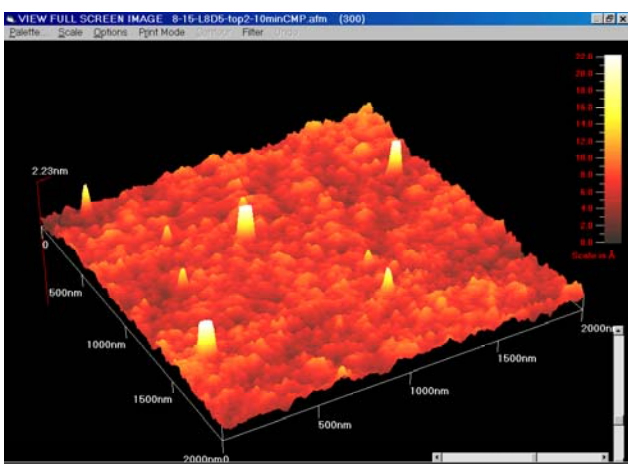


Figure 8. AFM image showing the surface roughness of a substrate after CMP Planarization. RMS roughness 0.2 nm.

A similar substrate after chemical mechanical polishing for 10 minutes is shown in Figure 8. The rms roughness has been reduced from 2.9 nm to 0.2 nm. The large individual peaks are probably debris.

Another method of planarizing sensor underlayers, especially between layers of metalization such as interconnects and on-chip coils have been deposited is to use spin-on organic insulators such as BCB. Figure 9 shows the cross section of an SDT sensor with several layers of metal for interconnects and field coils. Note the BCB insulation layers.

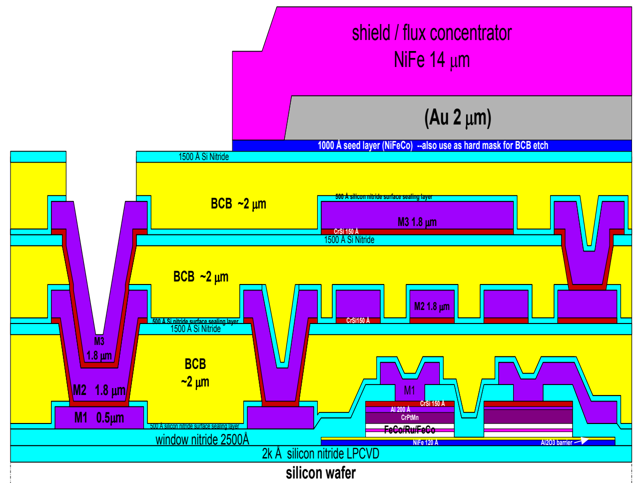


Figure 9. Cross section of SDT sensor showing BCB insulation used to planarize layers between metal depositions.

Signal Processing

A block diagram of the data acquisition system for monitoring a 16-element array such shown earlier is shown in Figure 10. Two 8-channel multiplexers (AD 7501 & AD 7503) are combined for 16-channel selection. This circuit is made possible by using multiplexers with the same specifications and pin configurations where one of them has an *enable* input that is active 'true' and the other is active 'false'. Because the output impedance is high in the disabled state, the outputs from the multiplexers can be directly connected. A host computer provides control using a *nonlatched* (no handshaking) digital signal using 4 bits of a single port on the AT MIO16X, series E, data acquisition board.

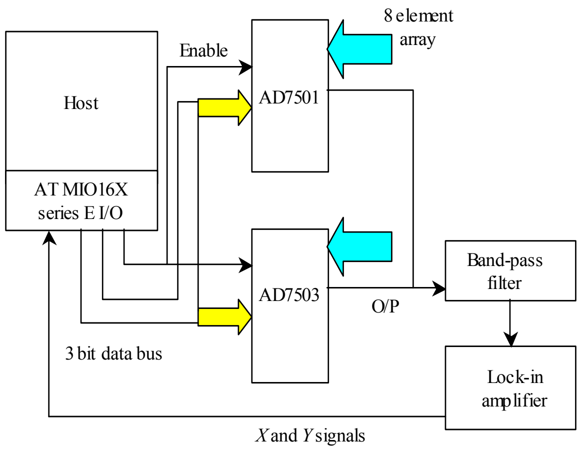


Figure 10. Block diagram of the multiplexed data acquisition system for multiplexing a 16-element GMR array.

Data acquisition systems can also include digitizers and control. The system shown in Figure 11 takes the signals from 64 sensors in an array for biosensing, multiplexes them to an amplifier, and digitizes them. The computer controls the current to an electromagnet which applies an ac magnetic bias to the sensing elements.

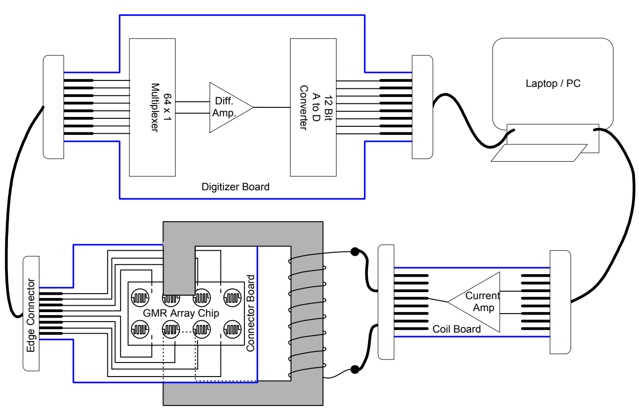


Figure 11. Data acquisition system for a 64-element biosensor array. Computer control of applied magnetic field is also shown

On-chip multiplexing of sensors reduces the number of connections to the chip. The multiplexing can be accomplished by using FETs to select the device to be connected to an external digitizer as is shown in Figure 12. Multiplexing can be accomplished by selecting the sensor to which the sensing current is directed or by using parallel sense current and multiplexing the output.

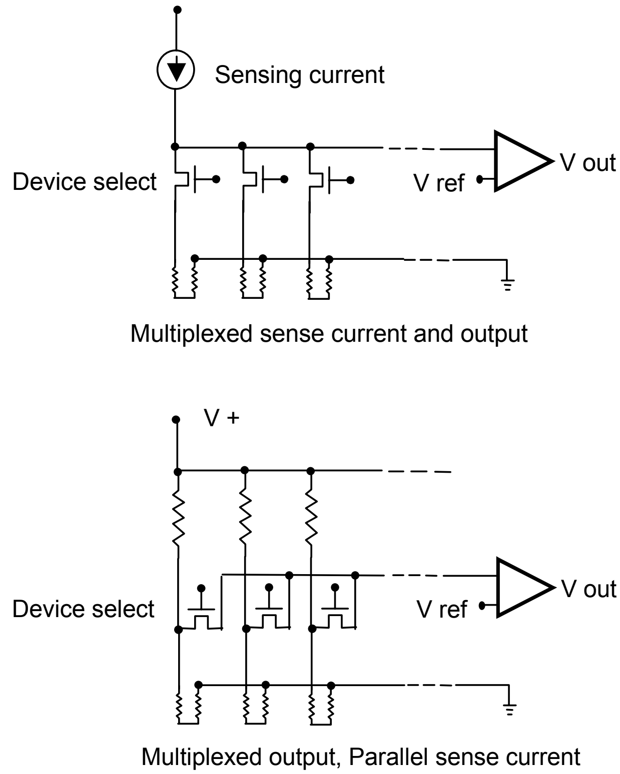


Figure 12. Schematics of multiplexed data acquisition by on-chip FETs. Either the sense current or the output can be multiplexed.

Applications

Imaging of magnetic media – There are a variety of applications that utilize arrays of magnetic sensors to form images of various types of magnetic media. Information recorded on audiotapes by simple tape recorders and even telephone answering machines has played important roles in legal cases. It is important to ascertain whether these recordings are genuine or have been edited. Direct imaging of the magnetic patterns on the tape surface can reveal starts and stops and erasures. In some cases, magnetic imaging can recover information that was erased and is no longer available in audio playback. The original information may remain as patterns bordering the erase head or even may be recovered as a faint image in the erased section. Research has been done at the National Institute of Standards and Technology (NIST) in Boulder, Colorado on methods to recover this seemingly lost information.[7] An image is slowly acquired one scan at a time using a commercial magnetoresistive read head from a computer hard drive. Magnetic sensor arrays can tremendously reduce the time to acquire such information and bring this technology out of the research laboratory and into the forensic laboratory.[8]

Magnetic imaging using high-resolution arrays of magnetic sensors has many potential uses in commerce.

Personal computers and high quality color printers and copiers have made detection of counterfeit currency an increasing worldwide problem.[9] 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 of currency presented to vending machines and bank sorting machines. The signature of additional magnetic information encoded into many counties' currencies can be used to distinguish valid currency from copies. At present magnetic signatures are read by one, or at the most a few, magnetic sensors as a bill passes a detection head. Optical detectors are used to obtain a more complete image of the bill. High-resolution GMR sensor arrays could obviate the need for optical imaging by providing a magnetic image of the bill.

The magnetic imaging of currency is difficult because the low fields produced by the magnetic ink. 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. Similarly, present commercially available magnetoresistive currency detection heads must be in direct contact with the passing 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 an image of one trace along the length of the bill or across the bill. Figure 12 shows a magnetic trace across the right half of a new U.S. $20 bill. The upright sections of the letters in the word "TWENTY" cause the multiple peaks in the center. The border surrounding the portrait causes the large peak on the right and the frame surrounding the bill, the peak on the left. The GMR sensor output is amplified by an instrumentation amp and an operational amp with a combined gain of several thousand. A low-frequency, high-pass filter and a high-frequency, low-pass filter limit noise and eliminate dc bias problems.

Credit card fraud is an increasing problem in many parts of the world. Skimmers use small computer devices to obtain the information from credit cards at ATM terminals and use that information to create bogus "clone" cards. These cards are then used at other ATM terminals to withdraw money. Methods of increasing the security of magnetic stripe credit cards include using higher resolution readers to read unique fingerprints in each card in the random arrangement of the magnetic particles or in random magnetic particles added to the plastic itself.[10] High-resolution magnetic sensors and magnetic sensor arrays are the basis for these security methods.

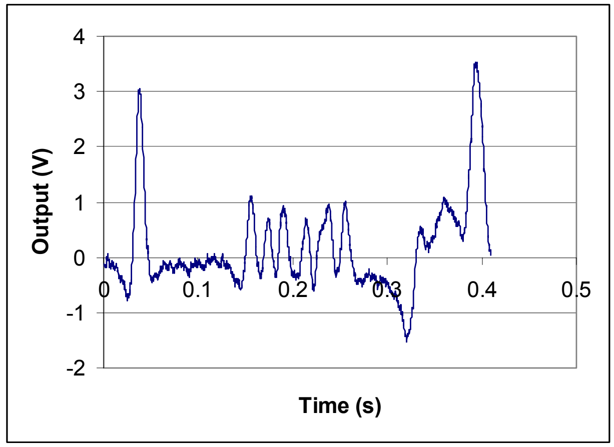


Figure 12. Amplified output from a GMR magnetic sensor when passed over the center of the right half of a new-style U.S. twenty-dollar bill.

The same method of using magnetic "noise" to increasing security of magnetic stripe credit cards can be applied to verifying the authenticity of personal identity cards and documents – vital to the increased security needs for Homeland Security.

Nondestructive Evaluation -- Solid-state magnetic sensors based on GMR and SDT effects have high, frequency-independent sensitivity that extends to the low frequencies necessary for deep, eddy-current penetration. The use of these sensors has been demonstrated in NDE detection and magnetic imaging of surface cracks and features, deep cracks, and cracks initiating from edges of holes.[11 12 13 14] The small size and low power consumption of these solid-state magnetic sensors allow them to be used in arrays of multiple sensors on a single chip facilitating rapid scanning of an area for defects in a single pass rather than by single-point, raster scanning.

The main components of an eddy current probe for NDE comprise a pancake-type coil and a GMR or SDT sensor. During measurement the sensing axis of the GMR or SDT probe is maintained to be coplanar with the surface of the specimen. The excitation field on the coil axis, being perpendicular to the sensing axis of the GMR or SDT films, has no effect on the sensor. In this way, the detected field, which is the result of the perturbation of the eddy current flow paths due to the crack, is separated from the excitation field. Due to the circular symmetry of the field produced by the coil, corresponding eddy currents induced in the surface of a defect free specimen are also circular. In this case, the tangential component of the field created by the eddy currents is zero at the location of the sensor. In the presence of defects, the probe provides an absolute measure of the perturbed eddy currents.

The size of the coil is related to the resolution necessary to detect the defects. For large defects and for deep defects, large coils surrounding the sensor are required. To resolve small defects, small coils located close to the specimen are necessary. It is possible to incorporate the excitation coils directly on GMR or SDT sensors.

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 or SDT 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 if the detector is raster scanned over the surface.

A prototype of an SDT based eddy current probe has been built and successfully tested for detecting cracks of calibrated width and depth. Figure 13 shows the output of such a probe. The asymmetry in the magnetic field is detected on either side of the crack when the sensitive axis is perpendicular to the crack. In the left figure, the asymmetry is detected at the ends of the crack when the sensitive axis is parallel to the crack. 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.

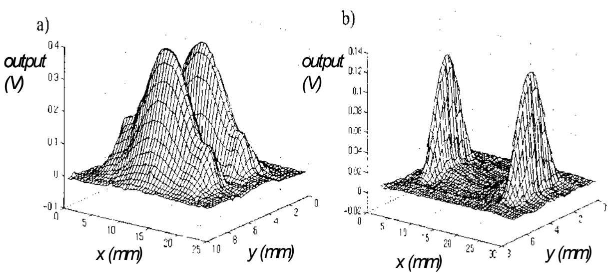


Figure 13. The output of an SDT eddy-current probe with 20 kHz excitation scanned over a 15 mm by 2 mm deep crack. a) sensitive axis parallel to the crack. b) sensitive axis perpendicular to the crack. (Results courtesy of Albany Instruments.)

SDT sensors are in attractive for NDE low frequency applications, such as for the detection of deeply buried flaws. In contrast, inductive probes have poor sensitivity at low frequencies because they are sensitive to the time derivative of the magnetic field rather than to the magnitude of the magnetic field created by the flaw. For detecting deep cracks, it is necessary to use large diameter excitation coils in order to increase the penetration depth of the eddy currents into the material under test. SDT eddy current probes were tested for detecting edge cracks at the bottom of both a single plate and a stack of thick aluminum plates. A short edge crack of 3 mm length and 3 mm height was detected at a depth of 18 mm below surface, and a crack of 15 mm length and 3 mm height was detected at 23 mm at the bottom of a two-layer aluminum structure. Figure 13 shows the results of a single scan along the edge and across the buried crack in both magnitude and phase representations.

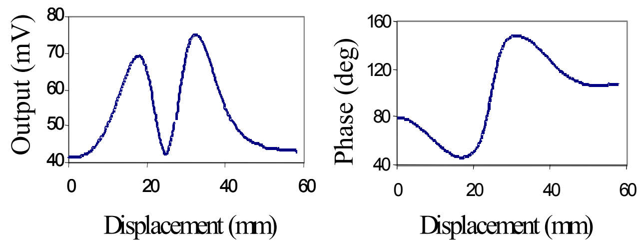


Figure 14. The signature of a 15 mm long edge crack 9 mm below the surface in both magnitude and phase of the output of an SDT eddy-current probe. Exciting frequency was 200 Hz. (Results courtesy of Albany Instruments.)

Aging aircraft must be inspected for defects that accumulate in the skin including cracks around rivet holes and corrosion between layers in multi-layer airframe skins. Eddy-current probes are of primary use for this nondestructive evaluation. For deep flaws, the low frequency response of GMR and SDT sensors make them ideal for this application. A demonstration of the capabilities of GMR-based eddy-current probes was carried out at Albany Instruments. For this experiment, pinholes of small diameters (1.0 and 0.75 mm) of different depth were detected on the backside of an aluminum plate of thickness 1.6 mm. Two rows of holes were machined in the bottom surface of the plate to simulate corrosion-type defects. The first row consisted of four holes of 1 mm (0.04 inch) diameter, the second one of four holes of 0.75 mm diameter (0.03 inch). The depths of the holes in each row were 1 mm, 0.75 mm, 0.5 mm and 0.25 mm. The space between holes in each row was 15 mm.

The goal of the experiment was to detect these defects from the opposite side of the plate. To obtain the penetration depth and the resolution required for this type of defects, an excitation coil of mean diameter of about 2 mm was chosen. The optimum detection of defects was obtained at the frequency of 8 kHz. A schematic diagram of the probe above the specimen during the experiment is represented in Figure 15.

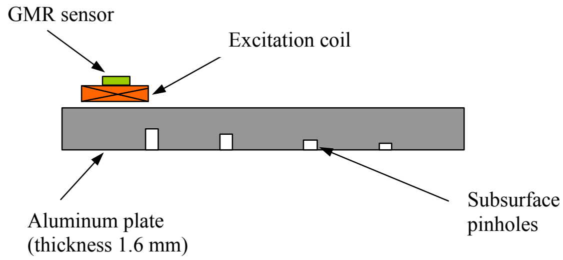
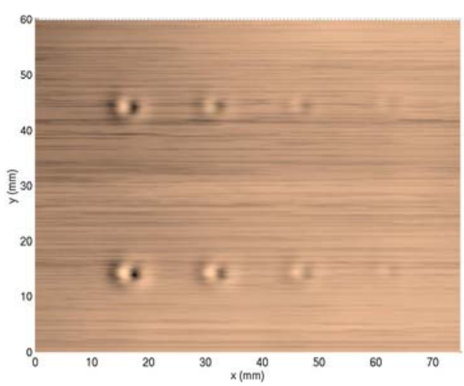


Figure 15. Schematic diagram of the experiment to detect hidden corrosion in metallic layers.

A raster scanning covering the region of both rows of holes is shown in figure 16. The magnitude and phase maps obtained are shown in Figure 16a and 16b. It can be observed that all buried holes are clearly visible in both plots. The smallest holes (0.25 mm depth) are better visible on the phase plot.

a.)



b.)

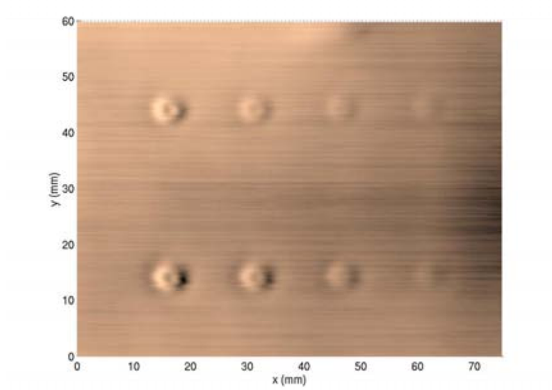


Figure 16. Maps of the Magnitude (16a) Phase (16b) of the sensor output from a two-dimensional scan of a specimen containing subsurface holes. The excitation frequency was 8 kHz. (Scan courtesy of Albany Instruments)

Precision Position Sensing – The same eddy current sensing capability used for non-destructive testing can be applied to precision position sensing. Very accurate position measurements can be made of a conductive target utilizing solid-state magnetic sensors based on GMR and SDT effects. The sensors high sensitivity and their high, frequency-independent sensitivity that extends to low frequencies provide a combination of effects that allow for very precise position sensing.

Figure 17. An eddy current–based precision position sensor and associated electronics (Picture courtesy of Lion Precision Inductive).

Magnetic bioassay -- 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.[15]

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.[16 17] 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 SOIC 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. 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.

In a proof of concept experiment an array of 80 x 5 µm GMR sensor elements was fabricated from sandwich GMR material.[18] 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.

An integrated GMR sensor can include the array of sensors, the processing electronics, the current straps that provide the field to magnetize the microbeads, and even the fluid handling microchannels on the same substrate. Figure 18 shows a cross section of such a sensor. Systems based on this technology can be developed to automatically analyze biological materials in the field without extensive laboratory equipment.

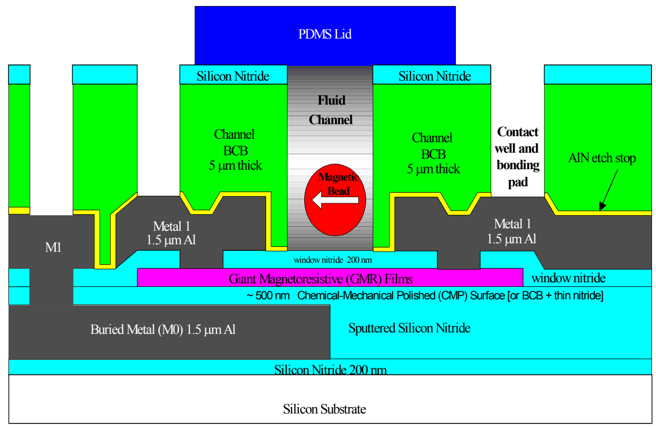


Figure 18. The state of the art at NVE for magnetic devices combined with microfluidics.

Figure 19 shows a biomagnetic IC experimental array, without fluidic channels developed by NVE for test by biotechnology companies.

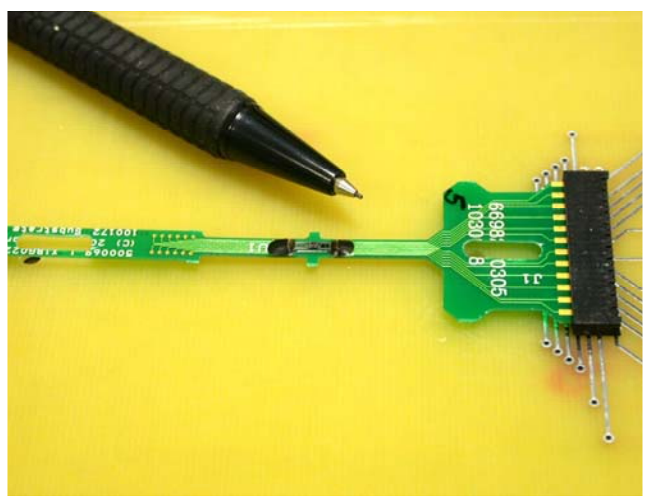


Figure 19. NVE's first biosensor array including the board. It consists of three different sized resistor bridges and three different sized discrete resistor arrays. These devices will be sampled to biotechnology firms in 2003.

Conclusion

The development of very dense on-chip magnetic arrays is still in its infancy. Although, there remains many technology issues to be resolved these issues are being confronted by many diverse organizations, both public and private. This technology is rooted in the same magnetic technology that is driving MRAM as well as both sensor nano-technology and MEMS so its future is bright. The list of potential applications continues to grow very rapidly, and exciting new opportunities are constantly emerging. Certainly, the number of companies entering this new area can be expected to expand rapidly. The applications highlighted in this presentation are at the forefront of current development. It is our belief that many more applications will emerge as the technology is proven out.

Acknowledgements

Parts of these results originated from research sponsored by the AFRL, NSF, NASA, DARPA, and NOAA. We also acknowledge contributions from our colleagues at NVE, Albany Instruments, and University of North Carolina at Charlotte.

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; Carl H. Smith and Robert W. Schneider, "Low-Field Magnetic Sensing with GMR Sensors, Part 1: The Theory of Solid-State Sensing," *Sensors Magazine*, vol. 16, no. 9, (September 1999), pp. 76-83; and Part 2: GMR Sensors and their Applications," *Sensors Magazine*, vol. 16, no. 10, (October 1999), pp. 84-91. (available online at www.sensorsmag.com)

[2] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, "Spintronics: A Spin-Based Electronics Vision for the Future," *Science*, vol. 294, (16 November 2001), pp. 1488-1495.

[3] D. Wang, J. Anderson, and J. M. Daughton, *IEEE Trans. Magn*. MAG-33**,** 3520 (1997).

[4] Robert Schneider, John Anderson, Mark Tondra, Cathy Nordman, Albrecht Jander, Zhenghong Qian, and Jim Daughton, "First results from packaged low-power Spin Dependent Tunneling sensors," Military Sensing Symposia, Adelphi, MD, September 24, 2002 (proceedings not in public domain)

[5] Carl Smith, Bob Schneider, and Arthur Pohm "High-Resolution, Chip-Size Magnetic Sensor Arrays," *Sensors Magazine*, vol. 20, no. 3, (March 2003), pp. 44-49. (available online at www.sensorsmag.com)

[6] 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. (available online at www.sensorsmag.com)

[7] David Pappas, "Imaged Audio Tapes Using Scanning Magneto-Resistive Microscopy*," Journal of Research of the National Institute of Standards and Technology*, Vol. 105, No.2, p. 334 (2000).

[8] P. Weiss, "Magnifier May Crack Crimes, Crashes," *Science News Online*, Vol. 158, No. 2, (2000).

[9] Carl Smith and Bob Schneider, "The Color of Money: Using magnetic Media Detection to Identify Currency," *Sensors Magazine*, vol. 18, no. 11, (November 2001), pp. 26-29. (available online at www.sensorsmag.com)

[10] Ann All, "MasterCard intros new way of fingering card fraud," ATMmarketkplace.com, February 13, 2003.

[11] B. Wincheski and M. Namkung,, in *Review of Progress in QNDE*, Vol. 18, Plenum, New York, 1999, p. 1177.

[12] T. Dogaru and S. T. Smith., "Detection of cracks near sharp edges by using giant magnetoresistance-based eddy current probe", *SPIE Proceedings*, 3994, 2000, p. 211.

[13] T. Dogaru and S. T. Smith, "A GMR based eddy current sensor," *IEEE Trans. Magn,* MAG-37, 2001, p. 3831.

[14] T. Dogaru., C. H. Smith., R. W. Schneider, and S. T. Smith, "New Directions In Eddy-Current Sensing Technology," *Sensors Magazine*, Vol. 18, no. 6, (June 2001), p. 56. (available online at www.sensorsmag.com)

[15] 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. (available online at www.sensorsmag.com)

[16] 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.*).

[17] 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).

[18] 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).