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CHIP-SIZE MAGNETIC SENSOR ARRAYS

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Abstract – Arrays of micron-sized magnetic sensors and sensor spacing on a single chip can be used to detect very small magnetic fields with high spatial resolution. These very small magnetic fields, or changes in magnetic fields, are associated with magnetic biosensors, non-destructive test/ inspection/evaluation, document validation including currency and credit cards and magnetic imaging. By using 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. Applications of these micro-arrays will be discussed during the presentation.

Introduction

Arrays of very small micron-sized sensors on a single chip are not a new phenomena. Arrays of visible light sensing diodes (photodiodes) were made available in the mid-to late 70s. One of the more exciting commercialization areas for these devices was auto-focus mechanisms associated with 35mm cameras. Initially, these were arrays of photodiodes on an integrated silicon substrate. This was followed by IR sensor arrays that were targeted at the same consumer market. The growth and sophistication of MOS technology that took place during this same period of time provided light-sensitive CCD arrays to handle the task of light sensing in a variable lens environment. The aforementioned technologies provided the basis for industrial proximity, distance and color sensing. The technology has continued to grow and expand, manifesting itself in the MEMS-based micro-bolometers used in night-vision applications.

Single-chip arrays of magnetic sensors however are new. These 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. The older solid-state magnetic technologies; Hall-effect and Anisotropic Magnetoresisitive (AMR) 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) it has become possible to manufacture such devices. 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. By using 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. These have become very important areas of application following the event of 9/11/01. This was evidenced by a recent DARPA solicitation "BioMagnetic Interfacing Concepts (BioMagneticICs)". Both the technology and applications of these micro-arrays will be discussed during the presentation.

Sensor Elements

Extended arrays require extremely small sensing elements that operate at low power levels. Magnetoresistive elements can be lithographically patterned to form of simple resistors, half bridges, or full Wheatstone bridges.

Single resistor elements are the smallest devices and require the fewest components. On the other hand, they have poor temperature compensation and usually require the formation of some type of bridge by using external components.

Half bridges take up twice the space but offer temperature compensation due to the fact that both resistors are at the same temperature. Half bridges can be used as field gradient sensors if one of the resistors is physically separated from the other by some distance. They can function as field sensors if one of the resistors is shielded from the applied field. The number of external connections to an array of *N* half-bridge elements can be as low as *N+2* including supply and ground.

Arrays of full bridges require four resistors per sensor. Small magnetic shields plated over two of the four equal resistors in a Wheatstone protect these resistors from the applied field and allow them to act as reference resistors. Since all resistors are fabricated from the same material, they have the same temperature coefficient as the active resistors. The two remaining resistors are both exposed to the external field. The bridge output of such a bridge is twice the output from a bridge with only one active resistor. The output for a 16% change in these resistors is approximately 8% of the voltage applied to the bridge. Arrays of full bridges require more chip area than simple resistors or half bridges. In addition they more interconnects and connections to the outside world. An array of *N* full bridges requires *2N+2* connections.

If there is sufficient room on the chip magnetoresistive materials can be made more sensitive by adding permalloy structures plated onto the substrate act as flux concentrators. The active resistors are placed in the gap between two flux concentrators. These resistors experience a field that is larger than the applied field by approximately the ratio D/l of the gap D between the flux concentrators to the length l of one of the flux concentrators. In some cases the flux concentrators are also used as the aforementioned shields by placing the two reference resistors beneath them

GMR and SDT Materials

The development of Giant Magnetoresistive (GMR) and Spin Dependent Tunneling (SDT) materials has opened up a new era of miniature, solid-state, magnetic sensors. These deposited, multi-layer materials exhibit large changes in resistance in the presence of a magnetic field. Their thin-film nature allows the fabrication of extremely small sensors using traditional photolithography techniques from the semiconductor industry. Since these sensitive films can be deposited on semiconductor wafers, integrated sensors can be manufactured that incorporate both sensing elements and signal processing electronics same chip. On-chip integration is especially important for single-chip sensor arrays. A single-chip, sensor array with a large number of sensors requires a correspondingly large number of off-chip connections unless on-chip multiplexing is utilized. The area of the bonding pads can dominate the chip area unless on-chip electronics are used.

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 is 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. A simple structure is shown in Figure 1.

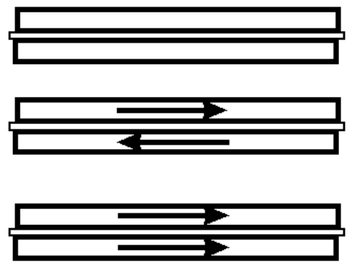

Figure 1. Scattering from two different alignments of magnetic moments in a GMR "sandwich" with two magnetic layers separated by a conducting non-magnetic layer.

Achieving parallel alignment of magnetic layers is easy. Just apply a large enough magnetic field. Achieving anti-parallel alignment requires more skill. One method is to place non-magnetic, conducting layers between the magnetic layers. If these layers are the proper thickness, a few nm, 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. Typical commercial multilayer materials exhibit maximum decreases in resistance of 10 to 20 % with applied fields of 50 to 300 Oe (4 to 2.4 kA/m). The curve of resistance as a function of applied field is shown in Figure 2. Note that the field decreases for either positive or negative fields.

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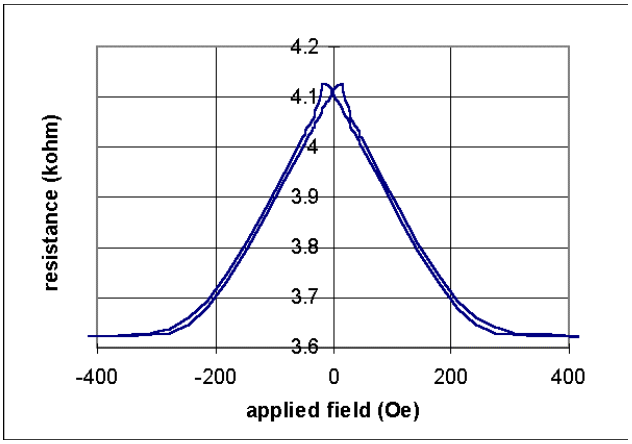

Figure 2. Resistance *vs*. applied field for a 2 µm wide stripe of mulltilayer GMR material. GMR = 14 %.

Spin dependent tunneling (SDT) structures are a recent addition to materials exhibiting a large change in resistance. In contrast to GMR structures, SDT structures utilize a thin insulating layer to separate 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 3 shows the layers of an SDT resistor manufactured using thin-film deposition.

The top layer of the stack is an IrMn antiferromagnet that pins the CoFe magnetic layer. The Al_2O_3 layer is the insulator, and the magnetization of the bottom layer of NiFeCo follows the applied magnetic field. The addition of an orthogonal bias field perpendicular to the direction of the magnetization of the pinned layer reduces hysteresis and results in a bipolar sensor. In the absence of an applied field, the direction of magnetization of the free layer is perpendicular to that of the pinned layer. Fields along the sense axis, which is parallel to the pinned layer, decrease that angle making the layers more parallel and decrease the resistance. Fields in the opposite direction increase the angle and increase the resistance.

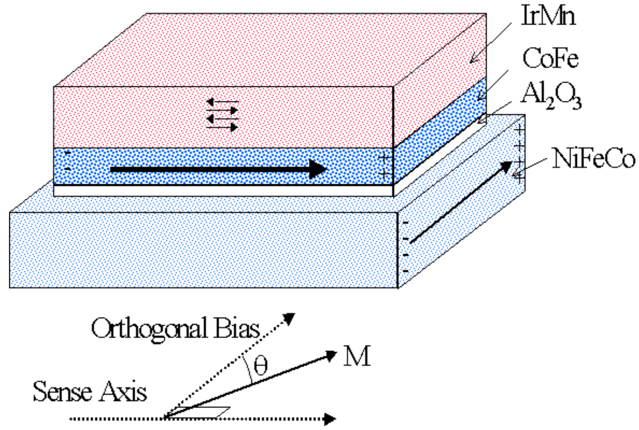

Figure 3. The layers and structure of an SDT resistor. The magnetization in the CoFe layer is pinned by the adjacent antiferromagnetic IrMn layer. The NiFeCo layer responds to an applied field along the sense axis and to an applied orthogonal bias field.

Changes of resistance with magnetic field of 10 to >40 % 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.

Sensor Arrays

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 and 2 and even 3 orthogonal directions over an extended area. A 2-D 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 and SDT sensors are ideal for array applications because of their very small size and low power requirements. Typical GMR multilayer material has a sheet resistance of about 10 ohms per square. This material can be photolithographically patterned into stripes 2 µm wide without significant magnetic edge effects. A 100 ohm resistor can be fabricated which is only 20µm long. Larger resistors can be fabricated by forming serpentine stripes of

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longer length. A 10 kΩ resistor can easily be fabricated in a 100μm square. These small dimensions are essential when multiple sensors are required for an array with high resolution.

The narrow stripes of multilayer material are sensitive to magnetic fields only along their long dimension. Demagnetizing fields prevent fields along their width or thickness from having a significant effect. The narrow stripes also allow arrays with much higher resolution than are possible with the older anisotropic magnetoresistive (AMR) materials. AMR materials are typically used in stripes 20 μm wide to sense fields transverse to the stripe. (See the first article in reference 1.) It is easy to see that much higher resistance and much more dense arrays can be made from the narrower GMR stripes.

For relatively large, coarse arrays, commercial GMR low-field sensors packaged in SOIC 8-pin packages can be placed on approximately 6 mm centers on circuit boards, individual 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 higher spatial resolution, arrays of GMR or SDT sensors with multiple sensing elements on a single die can be fabricated. One such array with 5 μm resolution covering a several mm width will be discussed later.

Linear Arrays

The simplest array is a one-dimensional array of sensors. These sensors are typically either single resistors or half bridges in order to fit them closely together. The sensitive direction is typically perpendicular to the spacing between sensors in the array since the sensitive direction is along the long dimension of the GMR stripes. Folded, serpentine resistors can be fabricated that have their sensitive axis parallel to the spacing between sensors.

An example of a simple array of resistors is shown in Figure 4 and the detail of the elements in Figure 5. This 16-element array has one sensor each 5 μm for a total width of 80 μm. The structures on each side are lap-line monitors to allow the array to be lapped to the end of sensor elements. This array was designed to image information stored on magnetic media by detecting the vertical component of the field with the sensor held immediately above a magnetic tape. The 1 mm by 2 mm size of this die is dictated by the number of bonding pads for the array and lap-line monitors.

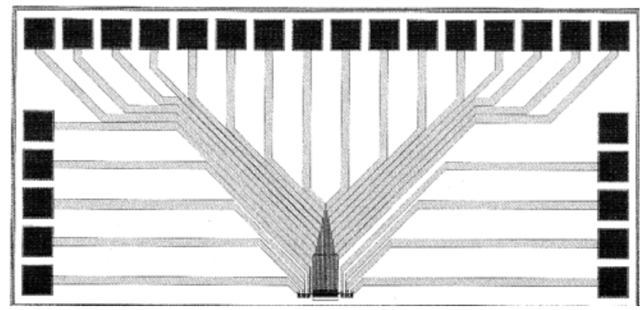

Figure 4. A 16-element array of resistor elements with 5 μm spacing. Structures shown on the sides are lap-line monitors.

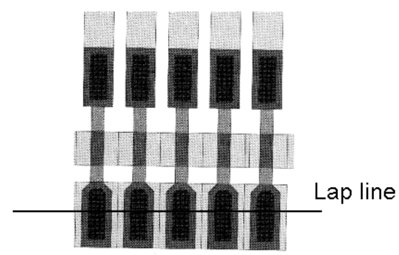

Figure 5. Individual elements of the 16-element array shown in Figure 4. The final lap line is shown.

The GMR stripes in Figure 5 are 1.5 are μm wide and 6 μm long so they have a resistance of about 40 ohms each. They have a common ground. A current strap runs transversely above them in order to apply a bias field.

A more sophisticated 16-element linear array of half bridges is shown in Figure 6 with the detail of the individual half bridges shown in Figure 7. This array has a common supply as well as a common ground while the center of each half-bridge in connected to a pad.

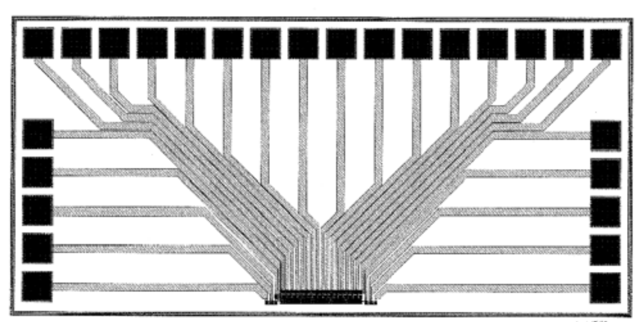

Figure 6. A 16-element array of half-bridge resistor elements with 15 µm spacing. Total width 240 µm.

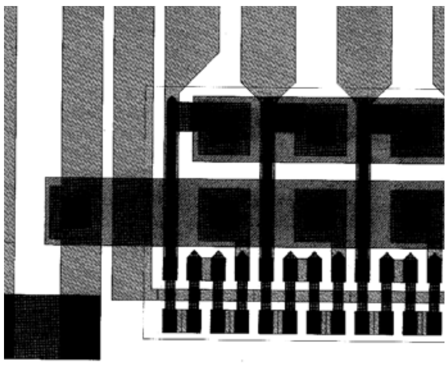

Figure 7. Individual elements of the 16-element half bridge array shown in Figure 6. Lower resistor elements are 4-stripe serpentine resistors with a repetition of 15 µm**.**

The GMR serpentine resistors in Figure 7 are 1.5 µm wide and have a total length of 18 µm so they have a resistance of 120 ohms each. The upper resistor of the half bridges are hidden under the connection to the center of the half bridge. The upper resistors consist of a single stripe 18 µm long. The 16-half bridges have a common ground which is attached to a pad on the left and a common supply which is attached to a pad on the right. A current strap runs transversely above them in order to apply a bias field.

As the number of sensor increases, so does the portion of the chip that is devoted to bonding pads for connections to the outside world. One method of reducing the number of pads is to connect the sensor elements together in a matrix. A 4.5 mm by 2 mm chip has been made with 128 single elements each 32 µm wide for a total width of 4.1 mm. The elements are arranged into two groups of 8 sets of 8 elements connected to 16 leads. Each set of 8 elements has a common ground pad. The other 8 pads are each connected to eight elements -- one in each set of eight. Two additional pads are connected to the biasing strap. Eight pads – four on each side – are connected to the lap line monitor structures. There are a total of 42 pads on the die. Eight of these pads will not be used after the die has been lapped.

To utilize such a matrix active feedback will maintain all of the other sensors in a group at the same voltage as that detected at sensor being measured. In this way, there is zero voltage difference between the sensor being measured and at least one node along each of the sneak paths. Therefore, no current can flow along the sneak paths and only the sensor being addressed is read.

The features of the new die can be seen more easily in the following figures. Figure 8 shows the matrix connections of one half of the elements, and Figure 16 shows the detail of the sensor elements themselves.

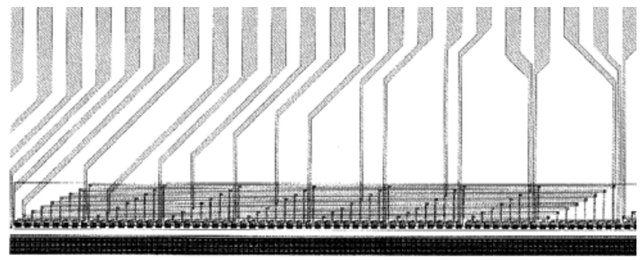

Figure 8. Left half of the 128-sensor matrix array. Each group of 8 sensors has a separate ground lead, and for each 8 sensors – one from each group – there is a separate supply lead.

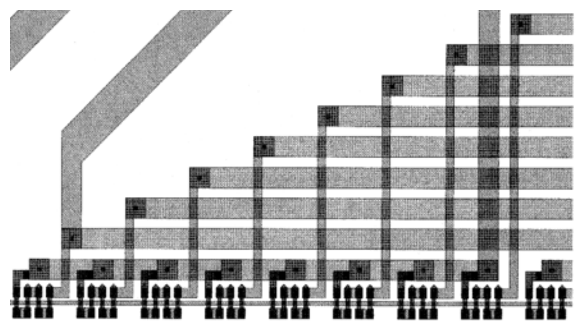

Figure 9. Left group of 8 sensor elements showing the serpentine connection of the 4 GMR stripes for each sensor, the bias strap, the common ground lead, and the connections to sensors in the other eight groups.

Linear arrays of GMR sensors can be used for detecting defects in ferromagnetic materials by detecting flux leakage due to the defects.[3] A one-dimensional scan using a 20-element GMR sensor resulted in a two-dimensional image.

Another type of array is the X-Y sensor, which uses two sensors to measure both the X-component of the field and the Y-component of the field at the same point. One such sensor is shown in Figure 10. Both sensors are full Wheatstone bridges with two active resistors and two shielded, reference resistors.

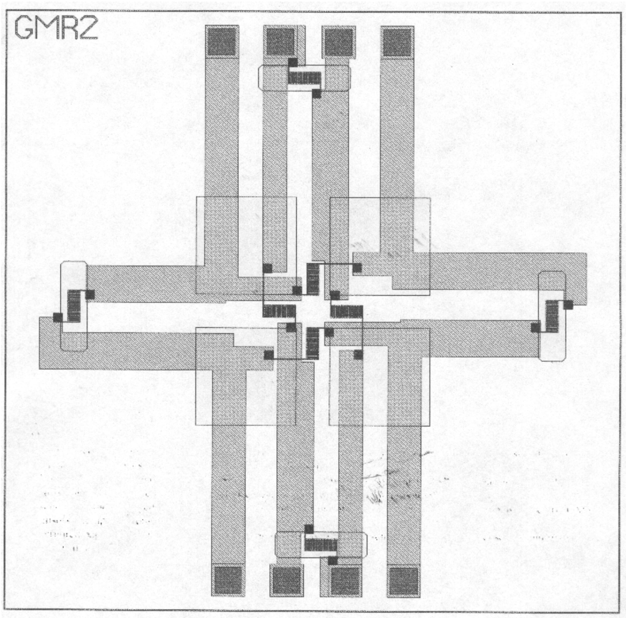

Figure 10. Composite diagram including all mask layers for two-axis multilayer GMR sensor. Plated NiFe shields are shown over the serpentine reference resistors near the periphery of the chip. The sensing resistors are shown in the center in the gaps between 3:1 flux concentrators

The serpentine sensing resistors (shown as black boxes in the diagram) are located between flux concentrators, and the reference resistors are located under shields. The sensitive direction of the resistors is transverse to their long dimension because the resistors are made up of multiple narrow stripes whose long dimension is transverse to the long dimension of the entire resistor. The interleaved sensor elements are connected as two independent Wheatstone bridges. This 2 mm by 2 mm die has room for larger flux concentrators than the 3:1 shown.

Two-dimensional arrays of sensors can be used to scan an area without requiring mechanical scanning if the area covered by the array encompasses the region of interest. Such a two-dimensional array of 2-D sensors is shown in Figure 11. In this array the GMR sensors are used in eddy current probes for crack detection in conducting materials.

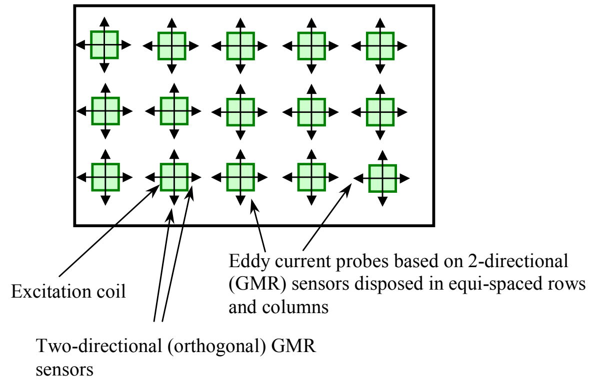

Figure 11. Two-dimensional array of eddy current probes based on 2-directional GMR sensors. The probes are equi-spaced in rows and columns

An additional use of two-dimensional arrays is to increase the resolution of a mechanically scanned array. If each row is offset from the adjacent row, it will cover a slightly different track. Figure 12 shows such a array with three rows of sensors to achieve a resolution three times smaller than a single row.

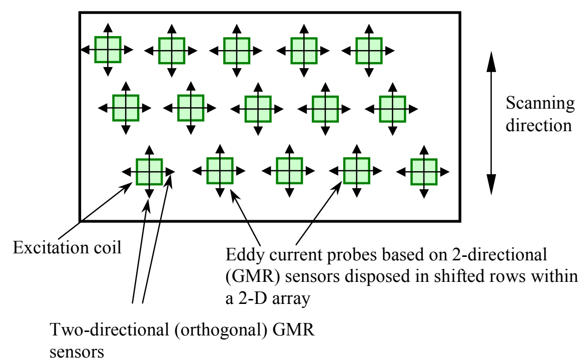

Figure 12. Two-dimensional array of 2-directional sensors (or eddy current probes) disposed in shifted rows to increase the spatial resolution of the defect mapping. The array requires a uni-directional scanning as shown in the figure.

Signal Processing

Smart sensors with both sensing elements and associated electronics such as amplification and signal conditioning on the same die are the latest trend in modern

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sensors. Sensor arrays have a large impetus for integration in order to minimize the number of connections when there are many sensors in the array. Multiplexing of outputs can minimize the number of connections from the sensor-array chip.

GMR materials are deposited on wafers with sputtering systems and can, therefore, be directly integrated with semiconductor processes. The small-size sensing elements fit well with the other semiconductor structures and are applied after most of the semiconductor fabrication operations are complete. Due to the topography introduced by the many layers of polysilicon, metal, and oxides over the transistors, areas can be reserved for GMR resistors with no underlying transistors or connections. Planarization of layers is another method of providing a smooth substrate for GMR materials. The GMR materials are actually deposited over the entire wafer, but the etched sensor elements remain only on these reserved, smooth areas on the wafers[4].

GMR materials have been successfully integrated with both BiCMOS semiconductor underlayers and bipolar semiconductor underlayers. The wafers are processed with all but the final layer of connections made. GMR material is deposited on the surface and patterned followed by a passivation layer. Windows are cut through the passivation layer to allow contact to both the upper metal layer in the semiconductor wafer and to the GMR resistors. The final layer of metal is deposited and patterned to interconnect the GMR sensor elements and to connect them to the semiconductor underlayers. The final layer of metal also forms the pads to which wires will be bonded during packaging. A final passivation layer is deposited, magnetic shields and flux concentrators are plated and patterned, and windows are etched through to the pads.

A block diagram of the data acquisition system for monitoring 16-element array such shown earlier is shown in Figure 13. 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.

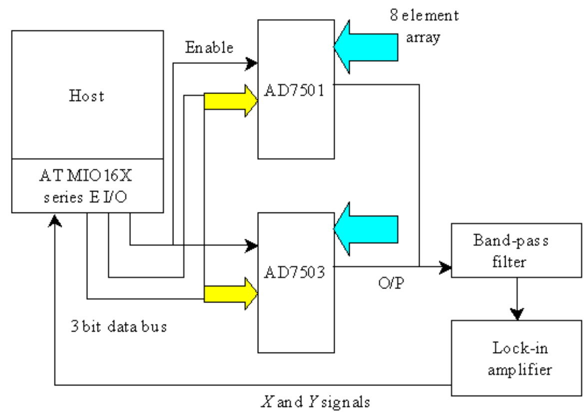

Figure 13. Block diagram of the multiplexed data acquisition system for multiplexing a 16-element GMR array.

Data acquisition systems can also include digitizers. The system shown in Figure 14 takes the signals from 64 sensors in an array for biosensing, multiplexes them to an amplifier, and digitizes them.

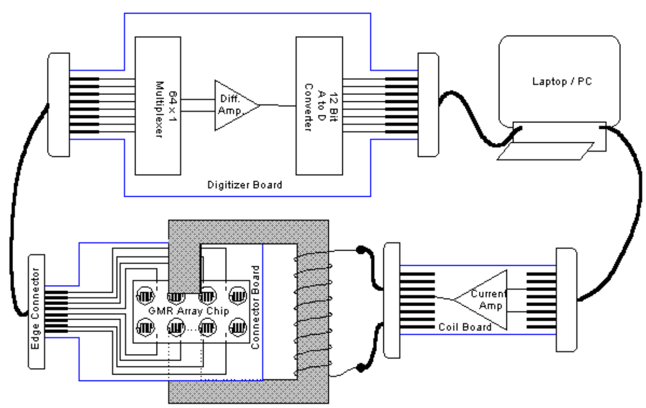

Figure 14. Data acquisition system for a 64-element biosensor array.

Applications

Imaging of magnetic media – There are a variety of applications which 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 have played important roles in legal cases. It is important to ascertain whether these recordings are genuine or have

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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.[5] 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.[6]

The recording tape recovered from flight data recorders and cockpit voice recorders after aviation crashes is not always in pristine shape. In fact in some occasions the information must be recovered from little scraps of tape. Magnetic imaging of these scraps using GMR sensor arrays offers a potential method of obtaining vital information that is now beyond the reach of practical read-back methods.

Magnetic imaging using high-resolution arrays of magnetic sensors have many potential uses in commerce. Personal computers and high quality color printers and copiers have made detection of counterfeit currency an increasing worldwide problem.[7] 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 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 several, magnetic sensors as a bill passes a detection head. In addition 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 along one line the length of the bill or across the bill. Figure 15 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.

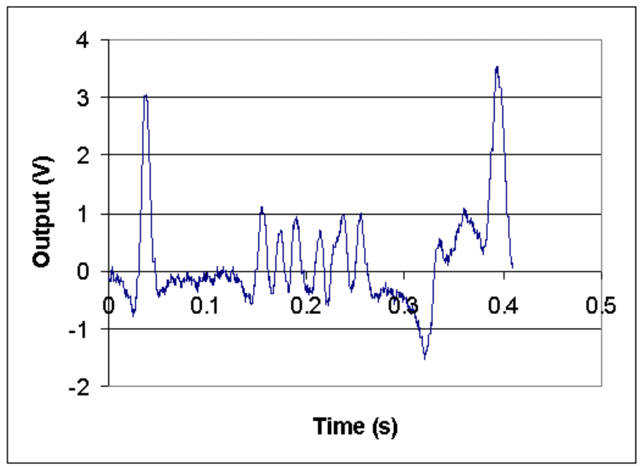

Figure 15. Amplified output from a GMR magnetic sensor when passed over the center of the right half of a new-style U.S. twenty-dollar bill.

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.[8]

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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.[9] [10] 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. 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.[11] 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 16 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.

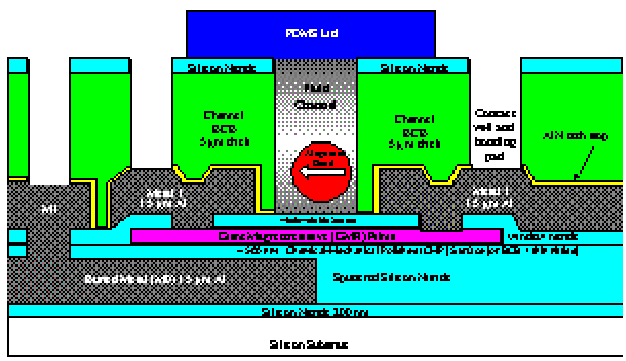

Figure 16. The state of the art at NVE for magnetic devices combined with microfluidics.

Non destructive testing – Eddy current methods are used in non-destructive evaluation (NDE), non-destructive inspection (NDI), and non-destructive testing (NDT) of conducting metals. Recent developments have included the use of GMR and SDT sensors to detect these eddy currents.[12]

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,

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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 may be 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 as the detector is raster scanned over the surface.[13] More rapid scans can be performed by using an array of detectors. In some cases an array of X-Y sensors could be left in place to monitor critical areas.

Magnetic couplers – Another application of arrays of GMR sensors on a single chip is that of magnetic couplers or isolators.[14] Magnetic couplers provide galvanic isolation between different circuits or nodes to eliminate ground loop problems. Magnetic couplers are analogous to optocouplers in a number of ways. Optocouplers transmit signals by means of light through a bulk dielectric that provides galvanic isolation. Magnetic couplers transmit signals via a magnetic field, rather than a photon transmission, across a thin film dielectric that provides the galvanic isolation. As is true of optocouplers, magnetic couplers are unidirectional and operate down to DC. But in contrast to optocouplers, magnetic couplers offer the high-frequency performance of an isolation transformer, covering nearly the entire combined bandwidth of the two conventional isolation technologies.

The input current is fed into an on-chip coil that produces a magnetic field. This field is detected by GMR sensors that are located immediately below the coil. The output of the sensors is used to drive output circuitry. The magnetic couplers can designed to handle either linear or digital signals. Due to the extremely fast response times of thin film magnetics, these couplers can operate at speeds up to 5 to 10 times faster than opto-isolators.

A quad-isolator with four GMR sensors, each with four individual GMR elements is actually an array of 16 sensing elements on a single chip. Figure 17 is a photomicrograph of such a chip. The sensor elements themselves are hidden under the stadium-shaped coils.

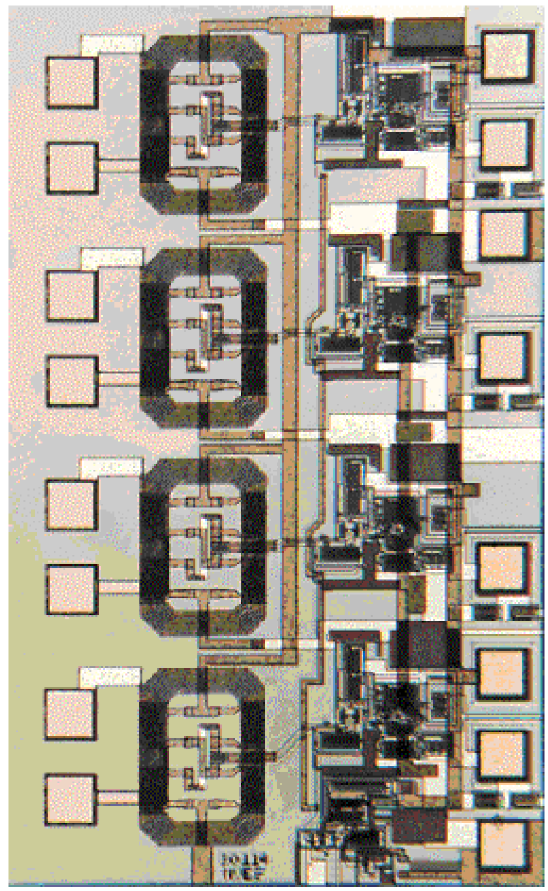

Figure 17. A four-channel magnetic coupler with a footprint of only 2.1 mm^2.

Summary

The development of the dense on-chip magnetic arrays is still less then ten years old. There are many technology issues to be resolved. Yet, the list of potential applications is growing very rapidly, and exciting new opportunities are constantly emerging. Rooted in the same magnetic technology that is driving MRAM, arrays of on-chip magnetic sensors are expected to continue to expand rapidly both in areas of application, as well as the number of companies that are supplying them. Certainly, the applications highlighted in this presentation are at the

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forefront of current development. It is our belief, that like light-sensing arrays, many more applications will emerge as the technology is proven out.

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