GMR MAGNETIC SENSOR ARRAYS FOR NDE EDDY-CURRENT TESTING

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ABSTRACT. Magnetic sensors based on Giant Magnetoresistance (GMR) and Spin-Dependent Tunneling (SDT) effects have high, frequency-independent sensitivity. The small size and low power consumption of these sensors allow them to be used in multiple-sensor arrays facilitating rapid scanning of an area in a single pass rather than raster scanning. This paper discusses the use of GMR and SDT sensors in NDE testing of surface cracks and features, deep cracks, and hole-edge cracks as well as progress in X-Y GMR sensors and multiple-sensor arrays.

INTRODUCTION

Solid-state magnetic sensors based on Giant Magnetoresistance (GMR) and Spin-Dependent Tunneling (SDT) effects have high, frequency-independent sensitivity that extends to low frequencies that are 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 [1-4]. 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. These sensors can be deposited on active silicon substrates thereby facilitating on-chip signal processing and multiplexing. This integration reduces the effect of noise, simplifies the sensor/signal-processing interface, and minimizes the number of leads.

Single-chip arrays of magnetic sensors are relatively new. 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. Older solid-state magnetic technologies such as Hall-effect and Anisotropic Magnetoresistive (AMR) were not able to be applied in these applications either due to size, power or sensitivity issues. With the advent of 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 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.

SENSOR ELEMENTS

High-resolution arrays with a large number of elements require extremely small
sensing elements that operate at low power levels. GMR materials can be lithographically
patterned in the form of simple resistors, half bridges, or full Wheatstone bridges.

Single resistor elements are the smallest devices and require the fewest
connections. They can be separate or can be connected in series with a differential
amplifier across each resistor. 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 some 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.

Full bridges require four resistors per sensor. Small magnetic shields plated over
two of the four equal resistors in a Wheatstone bridge 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 require 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 of the gap
\( D \) between the flux concentrators to the length \( l \) of one of the flux concentrators, \( D/l \). 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

Giant Magnetoresistive (GMR) and Spin Dependent Tunneling (SDT) 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. The fundamentals of GMR and SDT
materials have been covered in previous papers [5,6]. Only the basics will be 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.
Anti-parallel alignment can be achieved in alternating layers of magnetic and conductive materials if the conducting layers are the proper thickness. At a few nanometers thickness, the magnetic layers 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.

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. An antiferromagnet layer pins the adjacent magnetic layers. An Al₂O₃ layer is used for the insulator, and the bottom magnetic layer is free to follow the applied magnetic field. The addition of an orthogonal bias field perpendicular to the pinned magnetic 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.

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.

A comparison of magnetoresistive sensors is shown in Figure 1. Traces are shown for an AMR sensor, GMR sensors both with and without flux concentrators, and a prototype SDT sensor. The portion below 4 Oe is enlarged on the right. Note that the GMR sensors are omnipolar and can not tell the difference between positive and negative fields unless they are magnetically biased away from their zero.

![Figure 1](image.png)

**FIGURE 1.** Comparison of AMR, GMR, and SDT sensors. The portion of the traces below 4 Oe is enlarged at the right.
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 surface. In contrast, the information from a 2-D array of sensors tens of cm on a side can be used to image of a large area 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 patterned into stripes as narrow as 2 \( \mu m \) wide without causing significant magnetic edge effects. A 100-ohm resistor can be fabricated which is only 20\( \mu m \) long. Larger resistors or resistors sensing a wider area can be fabricated by forming serpentine stripes of longer length. These small dimensions are essential when multiple sensors are required for an array with high resolution.

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 anisotropic magnetoresistive (AMR) materials. AMR materials are typically used in stripes 20 \( \mu m \) wide to sense fields transverse to the stripe.

An example of a simple array of resistors is shown in the upper part of Figure 2. This 16-element array has one sensor each 5 \( \mu m \) for a total width of 80 \( \mu m \). 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 2.** A 16-element array of resistor elements with 5 \( \mu m \) spacing is shown in the upper portion. Total active width is 80 \( \mu m \). Individual elements of the 5 \( \mu m \) array shown on the right. A 16-element array of half-bridge resistor elements with 15 \( \mu m \) spacing is shown in the lower portion. Total active width is 240 \( \mu m \). Individual elements are shown on the right. The lower resistor elements are 4-stripe serpentine resistors with a repetition period of 15 \( \mu m \).
The GMR stripes for the array with 5 μm period in Figure 2 are 1.5 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 the lower part of Figure 1 with the detail of the individual half bridges shown on the right. This array has a common supply as well as a common ground while the center of each half-bridge is connected to a pad.

The GMR serpentine resistors 15 μm period in Figure 2 are also 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.

Linear arrays of GMR sensors can be used for detecting defects in ferromagnetic materials by detecting flux leakage due to the defects [7]. 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 3. Both sensors are full Wheatstone bridges with two active resistors and two shielded, reference resistors.

The serpentine sensing resistors (shown as black boxes in the diagram) are located between flux concentrators, and the reference resistors are located under shields (shown as oblong open boxes). 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.

![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](image)
APPLICATIONS OF SDT/GMR ARRAYS IN NDE

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 [3].

A prototype of an SDT based eddy current probe has been built and successfully tested for detecting cracks of calibrated width and depth [2]. Figure 4 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 4. 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.
FIGURE 5. Output from an SDT eddy-current probe with 30 kHz excitation frequency radially scanning two cracks on either side of a 6.4 mm hole in a 3 mm thick aluminum plate. Circle indicates the position of the hole.

A practical example of detecting edge defects is the detection of cracks initiating at the edge of a rivet hole. The specimen tested contains two real surface cracks, of length 2.65 mm and 2.75 mm respectively, occurring either side of a 6.4 mm diameter hole on a 3 mm thick aluminum plate. The cracks, being very thin, could not be observed visually. The test was performed by radially scanning the SDT probe over a ring containing the hole. The excitation frequency was 30 kHz. The sensitive axis was maintained in the circumferential direction to detect radial cracks. A 3-D map indicating the output voltage of the probe as a function of x-y position above the plate is shown in Figure 5 above. The map indicates two pairs of peaks, which correspond to the presence of two cracks. The cracks can be precisely located between these pairs of peaks.

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 6 shows the results of a single scan along the edge and across the buried crack in both magnitude and phase representations.

FIGURE 6. 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.
An image of an U. S. penny taken using a high-resolution GMR eddy-current probe is shown in Figure 7. The exciting frequency was 200 kHz, and the probe was raster scanned over the surface. This image demonstrates the ability of these probes to detect very small surface flaws and corrosion. The resolution of the image is about 0.1 mm in both directions.

**CONCLUSIONS**

Eddy-current probes based on GMR and SDT sensors have been shown to have promise in NDE applications including crack detection around rivet holes, deep flaw detection, and high-resolution surface-flaw detection. The frequency-independent response of these sensors allows them to be used with various excitation frequencies dictated by the depth of the flaw. Arrays of GMR sensors can scan an area in only one pass.

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