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Magnetoresistive Sensors for Nondestructive Evaluation

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ABSTRACT

New high-sensitivity solid-state magnetoresistive (MR) sensor technologies offer significant advantages in nondestructive evaluation (NDE) systems. A key advantage of MR sensors is a flat frequency response extending from dc to hundreds of MHz, making them particularly attractive for low-frequency and multi-frequency eddy current detection for deep-flaw detection and depth profiling. MR sensors are mass produced by thin film processing techniques similar to integrated circuit manufacturing, dramatically reducing the cost per sensor. The fabrication process is compatible with silicon circuit technology, allowing integration of sensors with on-chip signal processing. MR sensors can easily be produced in dense arrays for rapid, single-pass scanning of large areas. The small size and low power consumption of these solid-state magnetic sensors enable the assembly of compact arrays of sensors on a variety of substrates as well as on-chip sensor arrays. Arrays have been fabricated with sensor spacing as small as 5 μm. This paper presents a review of the state of the art in MR sensors and applications in NDE. The physical principles, manufacturing process, and performance characteristics of the three main types of MR devices, anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) are discussed. Their performance is compared to other magnetic sensor technologies for NDE applications. Finally, we provide a comprehensive review of the literature on NDE applications of MR sensors.

Keywords: nondestructive evaluation, magnetoresistance, multi-frequency, eddy current

1. INTRODUCTION

Nondestructive evaluation (NDE) is entering a new era in which solid-state magnetoresistive (MR) sensors are replacing traditional inductive sensors. MR sensors present opportunities for the development of new NDE techniques with enhanced capabilities, ease of use and lower cost. Research has already shown that MR sensors can provide higher resolution and deeper penetration for the detection and identification of hidden defects in structures. New areas such as corrosion detection and array sensors are being investigated. A comprehensive survey of the capabilities and limitations of MR sensors is presented here to help determine how best to apply MR technology to the specific problems of NDE.

2. MAGNETORESISTANCE

Magnetoresistance is the property of a material or system of materials that results in a change of resistance when exposed to a magnetic field. The discovery of large magnetoresistive effects has led to the development of solid-state magnetic sensors that can replace more expensive wire-wound sensors in a variety of applications.

All conductors exhibit a weak MR effect known as ordinary magnetoresistance (OMR) which is typically too feeble to be of use in sensors. Many magnetic materials, however, exhibit a larger magnetoresistive effect known as anisotropic magnetoresistance (AMR) which is significant enough to be used in sensors. Recent advances in thin film deposition technology has allowed researchers to create nanostructured multilayer devices with successively larger "giant" magnetoresistance (GMR) and tunneling magnetoresistance (TMR) effects. All three technologies are currently in use.

The usual figure of merit for magnetoresistance is the MR ratio traditionally defined by:

$$MR\% = \frac{R_{\max} - R_{\min}}{R_{\min}},$$

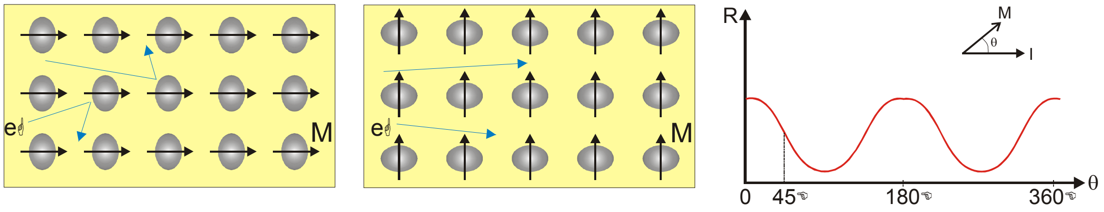
which, by this definition can exceed 100%. The MR ratio indicates the maximum signal that can be obtained from the sensor. AMR devices typically have MR ratios of 1-2%. GMR structures produce 20-50% MR while TMR commonly achieves 50-60%.

Anisotropic magnetoresistance (AMR)

Anisotropic magnetoresistance (AMR), discovered in 1857 by William Thomson (Lord Kelvin)[1] occurs in ferromagnetic materials. It is termed anisotropic because, in contrast to the previously known ordinary magnetoresistance, it depends on the angle between the electric current and the magnetization direction. The AMR effect is described as a change in the scattering cross section of atomic orbitals distorted by the magnetic field as illustrated in Fig 1. The resistance produced by scattering is maximum when the magnetization direction is parallel (i.e. 0° or 180°) to the current direction and minimum when the magnetization is perpendicular to the current. In general, the resistance is given as a function of the angle, θ, between the magnetization and current:

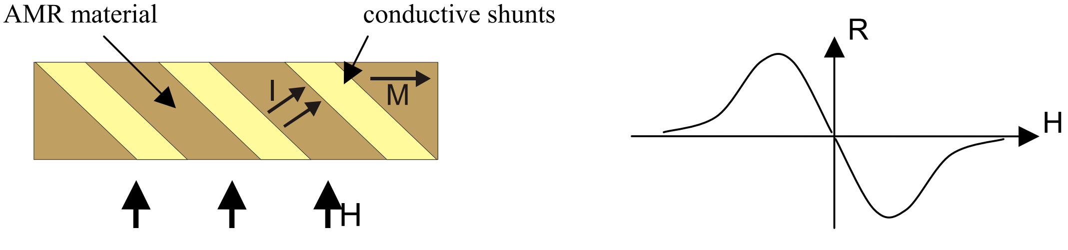
$$R = R_0 + \Delta R \cos^2(\theta)$$

This function, plotted in Fig. 1c, shows that the maximum sensitivity and linearity is achieved when the magnetization is at 45° with respect to the current. The 45° alignment is commonly achieved by patterning diagonal stripes of highly conductive metal onto the more resistive AMR material as shown in Fig. 2a. The current will then run perpendicular to these “barber pole” stripes while the magnetization vector remains preferentially along the long direction of the MR device. The application of an external magnetic field will rotate the magnetization with a resulting change in resistance as shown in Fig 2b. The MR ratio for AMR materials is typically a few percent. Integrated AMR sensors are commercially available.



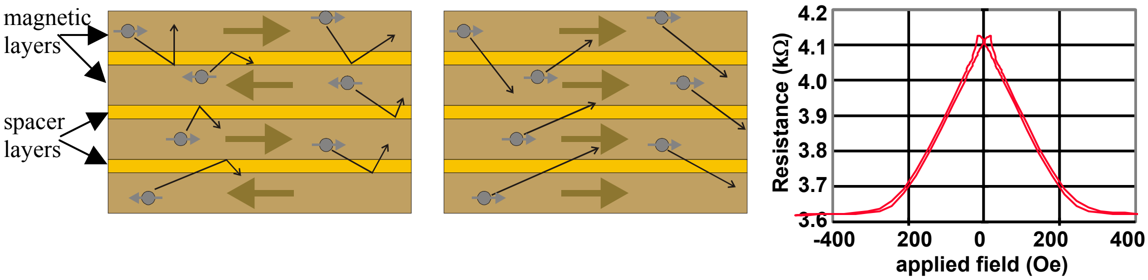
(a) (b) (c)

Fig. 1. Illustration of AMR effect showing distortion of electron orbitals and resulting difference in scattering when the magnetization is (a) parallel to the current or (b) perpendicular to the current direction. (c) Variation of resistance as a function of angle between the current and magnetization. The optimum operating point is at 45°.



(a) (b)

Fig. 2. (a) Barber-pole structure of conductive shunts that constrain the current to run at 45° to the rest position for the magnetization. (b) Resistance versus field for a properly biased AMR device.



(a) (b) (c)

Fig. 3. Illustration of the GMR effect with (a) layers of alternating magnetization producing lots of scattering and (b) reduced scattering when the magnetization of the layers is aligned by an applied field. (c) Resulting variation in resistance as a function of applied field.

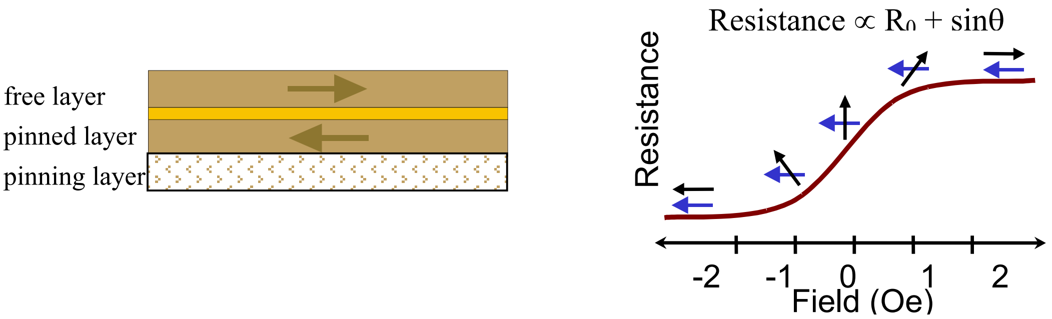
Giant Magnetoresistance (GMR)

The giant magnetoresistance effect in thin-film multilayers was discovered in 1988 by Baibich and coworkers at the Université Paris-Sud [2]. The term giant magnetoresistance was coined because the 10-15% change in resistance found in GMR far exceeds that of any AMR devices.

A GMR device consists of two or more layers of ferromagnetic metal (typically NiFe, CoFe or related transition metal alloy) separated by ultra-thin non-magnetic metal spacer layers (Cu, Au or Ru). To obtain the GMR effect, the spacer layers must be thin compared to the mean free path of electrons so that electrons spin polarized in one layer can pass into the other layers before their polarization is disturbed by scattering. Essentially, one can think of the ferromagnetic layers as polarizing filters for the spin of the electrons. The spacer layers allow the magnetic directions of the layers to differ while still permitting the passage of electrons. When the magnetic layers are aligned in the same direction, electrons originating in one layer may pass relatively freely through the other layers as illustrated in Fig. 3a. However, if the magnetizations are opposing, then electrons originating in one layer are blocked from the adjacent layer (Fig 3b). The disruption of the free motion of the electrons results in an increase in the electrical resistance.

GMR devices are typically operated with the sense current in the plane of the films (CIP, current-in-plane) using electrical contacts at the ends of long, often serpentine, lines. Although the magnetoresistance is reduced because of current shunting through the layers, the alternative current-perpendicular-to-pane (CPP) configuration will typically have a resistance that is too low for practical circuit applications.

The GMR effect is seen in multilayers of NiFe with Ru spacer layers. For sufficiently thin spacer layers only a few atoms thick, there appears a strong "exchange coupling" which tends to favor antiparallel alignment of the adjacent magnetic layers. Thus, in the absence of an externally applied field, the magnetic layers alternate in magnetization, resulting in a high resistance. When a magnetic field is applied, this can



(a) (b)

Fig. 4. (a) Structure of a spin valve. (b) Variation of resistance as a function of the applied field.

overcome the interlayer coupling and force all of the layers to align with the field and reduce the resistance. Since a magnetic field in either direction will cause alignment of the magnetizations, the resulting R vs. H curve is an even function, symmetric about zero as shown in Fig. 3c.

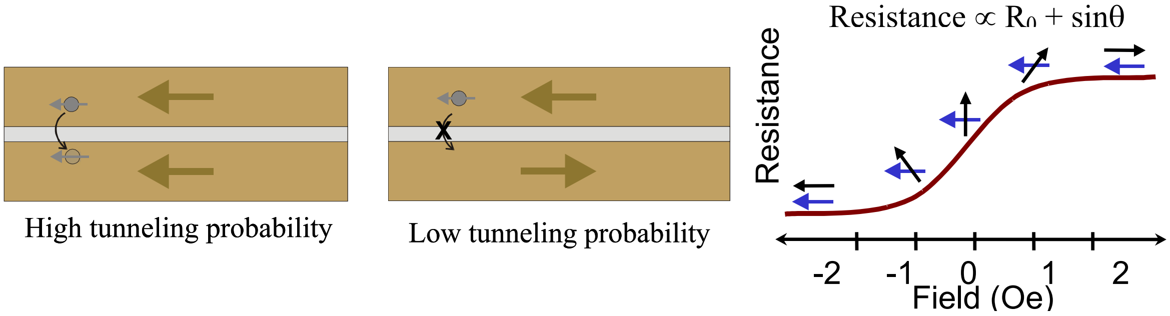
A modified version of the multilayer device uses only two magnetic layers as shown in Fig. 4. The bottom layer is deposited directly on top of an antiferromagnetic “pinning” layer. The antiferromagnetic layer has no net magnetization of its own, but tends to hold the magnetization of the adjacent ferromagnetic layer fixed in direction. The other layer is free to rotate its magnetization in response to a field. This structure has been termed a “spin valve” as one can imagine the magnetic field turning the upper layer like a faucet valve to control the flow of spin-polarized electrons through the device. In a properly biased spin valve the rest position of the free layer is made to be perpendicular to the pinned layer so that maximum sensitivity and signal swing is achieved. The response to a magnetic field applied in the direction of the pinned layer is linear over a fairly broad range. The resulting R vs. H function is odd and passes through zero.

GMR devices are used in read heads of hard disk drives. General-purpose commercial devices are fabricated by NVE Corp. Although improvement in sensitivity of GMR devices has slowed, conceivably, advances in materials with high spin polarization could result in significant enhancement of sensitivity.

Tunneling Magnetoresistance (TMR)

Tunneling Magnetoresistnace (TMR) structures are a recent addition to materials exhibiting a large change in resistance. TMR structures are similar to spin valves except that they utilize an ultra-thin insulating layer to separate two magnetic layers rather than a conductor. Electrons pass from one layer to the other through the insulator by quantum mechanical tunneling. The ease of tunneling between the two magnetic layers is modulated by the angle between the magnetization vectors in the two layers. When the magnetization of the layers is aligned many states are available in the bottom layer for spin-polarized electrons from the top layer to tunnel into. When the magnetization directions are opposite, the spin-polarized electrons are prevented from tunneling because they have the wrong orientation to enter the bottom layer. The process is also known as spin-dependent tunneling (SDT).

TMR devices use the spin valve arrangement of a pinned magnetic layer and a free magnetic layer. 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. TMR devices are operated in the CPP configuration with contacts on top and bottom of the film stack. Multiple TMR devices are often electrically connected in series to increase the



(a) (b) (c)

Fig. 5. Illustration of spin dependent tunneling. When the layer magnetizations are aligned (a) electrons from the top layer can find many available states in the bottom layer to tunnel into. When the magnetizations are opposite (b) then the majority electrons in the top layer can not tunnel into the bottom layer. (c) The resistance response is similar to GMR spin valves but larger in amplitude.

overall resistance and limit the voltage at each tunnel barrier. Voltages above a few hundred mV may damage the thin insulator.

Changes of resistance with magnetic field of up to 70% have been observed in TMR structures[3]. 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.

TMR technology is being developed for hard-disk read heads and advanced magnetic random access memories (MRAM) These applications will continue to drive research and development. Prototype general purpose TMR sensors have been produced by NVE Corp. but are not yet in commercial production.
TMR technology is in its infancy and significant advances may be expected in the coming years. Active research continues in the improvement of sensitivity as well as in understanding and reducing the excess noise at low frequencies. Two groups have recently announced results promising 200% MR ratios using MgO in the tunnel barrier instead of the usual Al_2O_3 [4, 5].

3. MAGNETORESISTIVE DEVICE CONFIGURATIONS

Flux concentrators

Magnetoresistive sensors can be combined with on-chip soft magnetic flux concentrators as shown in Fig. 6. The flux concentrators serve multiple purposes. They increase the sensitivity of the device by directing the magnetic flux lines towards the MR element positioned in the gap between the concentrators. They enhance the directionality of the sensor by amplifying only the magnetic field in the sensitive direction and shunting the field past the MR element in the transverse direction. The thin film anisotropy prevents the magnetization from rotating out of the film plane making MR sensors naturally insensitive to magnetic fields perpendicular to the surface. Additionally, the flux concentrators can also be used to shield half of the MR elements in a Wheatstone bridge from the influence of the magnetic field. The shielded elements are used as reference resistors to reduce sensitivity to temperature and supply voltage. For two-axis vector magnetometers, the flux concentrator can be split two ways as seen on the experimental GMR sensor shown in Fig. 6b. The MR elements are placed in the gaps between the four square concentrators.

Integrated coils:

Continuing the trend towards integration, thin film micro-coils can be patterned onto the same substrate as the sensors. The on-chip coils can be used either to buck the field from the eddy current excitation coil or to null the sensor in a feedback system. This extends the linear operating range of the sensor and avoids

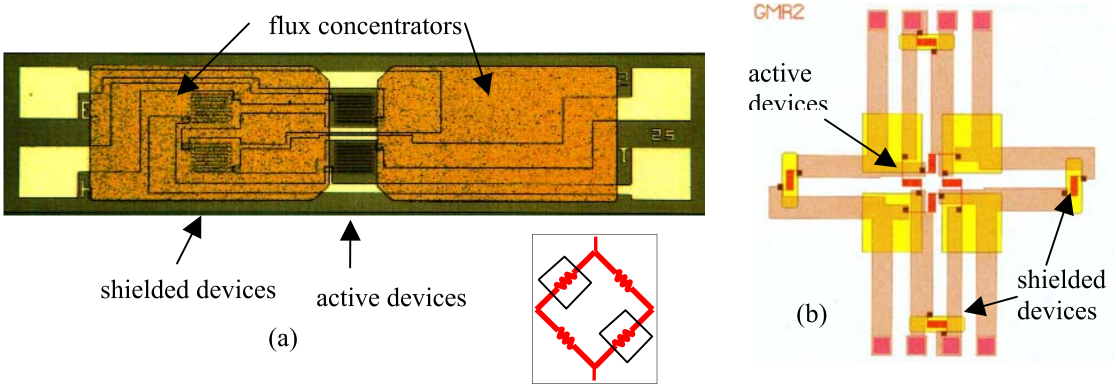


Fig. 6. (a) Microscope picture of a GMR sensor with integrated flux concentrators. The magnetic flux is concentrated on the devices within the gap. The other two devices are shielded from the external field. (b) Flux concentrator arrangement for a two axis sensor.

saturation. The coils are laid over the thin film sensors with the return path underneath the flux concentrators.

Fabrication

Magnetoresistive sensors are fabricated by thin film deposition, photolithography and etching techniques very similar to the process used to make integrated circuits. Many hundreds of identical sensors are built simultaneously on silicon wafers before being sawed apart and packed individually in standard electronic circuit packages for mounting on circuit boards. The massively parallel processing produces sensors with reproducible characteristics at very low cost.

Because the process is so similar to integrated circuit manufacture and the process steps are not damaging to silicon circuits, MR sensors can be built directly on top of and interconnected with integrated circuit wafers to combine sensors and circuitry in a single unit.

Arrays of sensors:

The ability to manufacture large numbers of identical sensors in a cost effective batch process opens the door to implementation of large arrays of sensors to facilitate rapid scanning of surfaces. This can be in the form of a linear array for scanning over a surface to form an image, or even a two-dimensional array that can image a particular area all at once.

In any large array of sensors, the wiring of sensors to the signal conditioning amplifiers and data acquisition becomes a problem because of the large number of interconnects needed. With the ability to integrate MR sensors with semiconductor circuitry, it becomes possible to provide signal conditioning, filtering, multiplexing and even digitizing right at the sensor, eliminating much of the wiring from the sensor head to the data processing unit.

4. PERFORMANCE OF MR SENSORS

Although researchers in the field proudly cite ever increasing MR ratios, a more useful metric for sensor applications is the sensitivity or the relative change in resistance per magnetic field usually given in units of percent per oersted. Ultimately, what really matters is the detectivity, or the minimum signal amplitude that can be detected. The detectivity depends both on the sensitivity as well as the background noise level of the sensor. Detectivity is defined as the signal amplitude for which the signal-to-noise ration is equal to one. While the sensitivity of MR sensors is generally independent of frequency over a frequency range covering dc to several MHz, most MR devices have reduced detectivity at low frequencies because of noise sources with a 1/f characteristic. At high frequencies, the detectivity is limited by Johnson noise inherent to the resistance of the device. Below a corner frequency that varies from device to device, the low frequency noise exceeds the Johnson noise. The corner frequency typically appears around 10 Hz to 10 kHz. The low frequency noise can be due to magnetic instabilities in the ferromagnetic layers of the sensor or due to charge states that vary the conductivity of the device over time. The characterization and mitigation of these noise sources is an ongoing area of research.

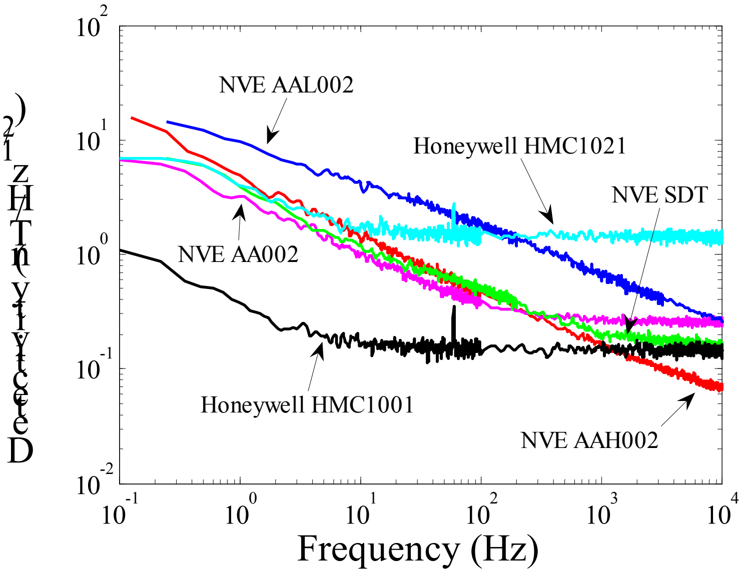


Fig. 8. Detection thresholds based on sensitivity and sensor noise as a function of frequency for several commercially available magnetoresistive sensors. The Honeywell sensors are based on the AMR effect. The NVE AA series sensors use GMR technology. The performance of a prototype SDT sensor is also shown. (Courtesy Steve Russek of NIST.)

While Johnson noise depends only on the resistance of the device, the excess low frequency SNR generally improves with the square root of the device volume. Thus, a technology with lower sensitivity may perform better at low frequency if it is inherently less noisy or if a larger volume of sensitive material is used. The thicker films of AMR sensors tend to have less excess noise than the thin-film multilayers of GMR and TMR devices.

Several commercially available magnetoresistive sensors have recently been characterized by the National Institute of Standards and Technology [6]. Fig. 8 shows the measured detectivity of these sensors as a function of frequency. Since the devices compared all have different sensor volume, this does not necessarily imply that one particular technology is better than another. While the AMR sensors perform as well or better than the more advanced technologies there seems little scope for improving their performance beyond what has been achieved. GMR and TMR technology, on the other hand is still improving both in terms of achieving higher sensitivity as well as developing processing methods that reduce the excess noise.

5. LIMITATIONS OF COMPETING TECHNOLOGIES

In order to justify the application of new technologies such as MR sensors it is helpful to investigate the limitations of existing and competing sensing technologies.

Inductive Sensors

Induction coil sensors have long been the mainstay in NDE. Consisting only of a coil of wire and possibly a soft magnetic core, their response function is easy to characterize from basic physical laws of induction. By Faraday's law, the voltage induced in the coil is simply:

$$V_{signal} = N\pi r^2 \frac{dB}{dt} \propto N r^2 f$$

where N is the number of turns of wire, πr^2 is the area of the loops and dB/dt is the rate of change of magnetic field which is proportional to the operating frequency, f. Clearly the signal amplitude can be increased by increasing the number of turns of wire in the coil. However, the resistance of the coil will increase because the total length of wire increases leading to additional resistance noise. Following scaling rules outlined by Korepanov[7], if the overall coil geometry is maintained constant then the cross sectional area of the wire must be decreased proportionally to *N* by using a different wire gauge. The resistance for a given geometry then goes as $2\pi rN^2$. If we reduce the size of the coil by decreasing all dimensions (including wire diameter) proportionally to *r* then the resistance will scale according to

$$R = 2\pi N^2 / r \; .$$

The sensitivity of an inductive coil is limited by Johnson noise given by

$$V_{noise} = \sqrt{4k_B TR\Delta f} \propto N / \sqrt{r} \; .$$

From this we see that the signal-to-noise ratio of an inductive coil for a given geometry is independent of *N* but decreases with the characteristic dimension, *r*, of the coil:

$$SNR = V_{signal} / V_{noise} \propto r^{5/2} f \; .$$

Because the SNR of inductive coils decreases rapidly with reduction in coil size and also decreases linearly with frequency, inductive pickups become less effective for high resolution and low frequency applications.

In practice, the coil must have enough windings to ensure sufficient signal amplitude so that the performance is not impacted by amplifier noise. Optimal induction coils are still wound by hand or by machine from copper wire. Although planar coils can be fabricated by photolithography, the limitation to planar geometries and low winding density invariably results in less-than-optimal performance for a given size coil.

Hall-Effect Sensors

The Hall effect is due to the Lorentz force that affects the trajectory of electrons in a magnetic field. In a Hall device, a voltage proportional to the magnetic field is produced across a current carrying conductor or semiconductor. Hall sensors are inexpensive and are easily combined on-chip with integrated circuitry. However, Hall devices typically have much lower sensitivity than MR devices and are being replaced by these. Hall sensors measure the magnetic field component perpendicular to the device plane as opposed to the in-plane sensitivity of MR devices. In some cases this geometry is preferred.

Hall-effect sensors have been used successfully in NDE applications. Their main drawback is limited sensitivity.

Superconducting Quantum Interference Devices (SQUID)

The most sensitive magnetometers are superconducting quantum interference devices (SQUID). These devices take advantage of the unique quantum mechanical properties of loops of superconducting wires. SQUID magnetometers can detect individual quanta of magnetic flux, giving them sub-femtotesla resolution. SQUID sensors have exceptional low-frequency stability. NDE using SQUID sensors has been demonstrated in a variety of configurations. The sensitivity and stability of SQUID magnetometers has even allowed the detection of electrical currents produced by active corrosion.

The main drawback of SQUID devices is that they require cryogenic cooling to below the superconducting transition temperature. This is provided either with a closed cycle refrigeration system or using cryogens such as liquid helium and nitrogen. The cost and maintenance associated with the cryogenic system is prohibitive in all but the most demanding applications. SQUID magnetometers are used, for example, in magnetoencephalography to image electrical currents in the brain, arguably an example of NDE that warrants the cost of employing this expensive technology.

6. APPLICATIONS IN NONDESTRUCTIVE EVALUATION

Magnetoresistive sensors have been employed in several experimental NDE systems but are not yet used routinely in practice. We review some of the implementations and experimental results here to demonstrate the potential of MR sensors in areas that take advantage of their specific features such as low frequency sensitivity, directionality, high spatial resolution and array configurations.

Eddy Current NDE

Eddy current NDE works by inducing electrical currents in the structure under test by applying time varying magnetic fields. Cracks or flaws within the structure distort the flow of these eddy currents which can be detected with sensitive magnetometers. The penetration of time varying magnetic fields into the sample is limited to the skin depth

$$\delta = \sqrt{1/\pi f \mu \sigma}$$

where f is the excitation frequency and μ and σ are the magnetic permeability and conductivity of the material respectively. For example in aluminum ($\mu = 1$ and $\sigma = 1/2.65$ μΩ-cm), in order for the eddy currents to reach a depth of 1 cm, the frequency would need to be below 80 Hz. At these frequencies, MR sensors can easily outperform inductive sensors of similar size.

Because of their wide bandwidth and good low-frequency response, MR sensors enjoy a particular advantage when low-frequency, multi-frequency or pulsed excitation is required for detection of deeply buried defects[8].

Sikora *et al*. at the Technical University of Szczecin, Poland have detected simulated cracks on the back side of 20 mm thick aluminum plates using magnetoresistive sensors and multi-frequency excitation ranging from 20 Hz to 120 Hz[9-11]. The simulated flaws were 0.5 mm wide and 4 mm deep.

Dogaru and Smith at the University of North Carolina have used the directionality and spatial resolution of GMR sensors to good effect to locate and characterize small surface[12] and edge[13, 14] cracks in aluminum specimens.

Perry *et al*. were able to image surface cracks in ferrous materials using 10 Hz excitation and AMR sensors[15]. More recently, Perry demonstrated a low cost system with off-the-shelf components that uses frequencies ranging from 20 Hz to 150 Hz to detect simulated cracks near fasteners in the third layer of a three layer stack of aluminum plates (6.3 mm, 12.7 mm and 6.3 mm thick).

Wincheski *et al.* at NASA's Langley Research Center demonstrated the use of GMR sensors in eddy current probes to image flaws in the 10th layer of 13 layers of 1 mm thick aluminum plates. Their system used an excitation frequency of 185 Hz and a novel self-nulling probe to prevent saturation of the magnetoresistive sensors.

Another difficult NDE problem is the detection of deeply buried cracks adjacent to fasteners in multilayer airframe joints. Several groups have addressed this problem with eddy currents probes using magnetoresistive sensors [16-18]. The NASA Langley group has developed a novel orbiting eddy current probe[19] with a GMR sensor to inspect such fasteners. Their system is shown if Fig. 9.

A further interesting application, where the high spatial resolution of the GMR probes has proven advantageous, is in the evaluation of metal medical implants for invisible cracks [20].

The relatively high spatial resolution of GMR sensors was also used for eddy current inspection of printed circuit boards. The system employed a thin film excitation coil with an x-y scanner and was able to detect defects as small as 50 μm wide within circuit traces.

The low-frequency and multi-frequency eddy current techniques enabled by MR sensors are particularly useful in the detection of hidden corrosion. Corrosion typically produces a gradual thinning or roughening of structures that can be difficult to image with conventional techniques. The use of multiple frequencies allows simultaneous measurement of several variables from which subtle changes in thickness of the sample can be estimated even with variations in probe-to-sample distance. With low frequencies it may even be possible to identify thinning in second or third layers of multi-layer structures. Several groups have begun research in this area, including Raymond Rempt at Boeing [21] and the ongoing investigations in Dayton, Ohio [22, 23].

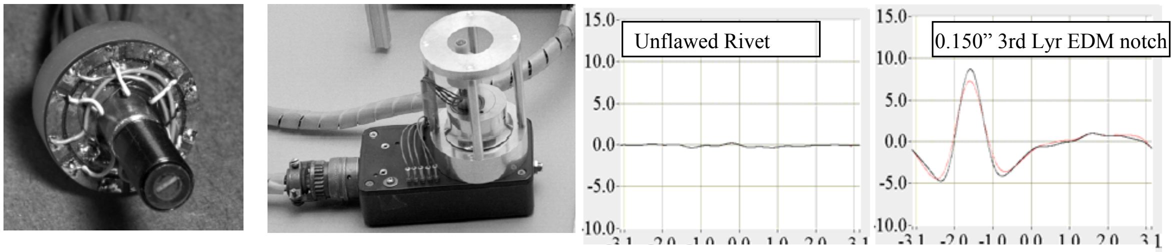


Fig. 9. Orbiting GMR eddy current probe for detecting flaws around rivets in aircraft lap joints. A small crack in the third layer is easily identified in the response.

Stray field sensing

At the very low end of the frequency scale, the dc response of MR sensors can be used to map out stray fields from defects in magnetic samples. The high resolution of small MR sensors even allows the observation of magnetic domain structure in grain-oriented transformer steel as an indicator of material quality[24, 25]. With the sensor scanned 35 μm above the surface, they observed domain structure with roughly 50 μm resolution in one dimension. Lo *et al.* of Iowa State University also experimented with inspection of sheet steel by observing local variations in the hysteresis response of steel using GMR sensors[26]. Their operating frequency, however, was between 10 kHz and 100 kHz.

Another group has used MR sensors to map out flaws by the disturbance of DC electrical currents injected directly into the structure[27].

Remote condition monitoring

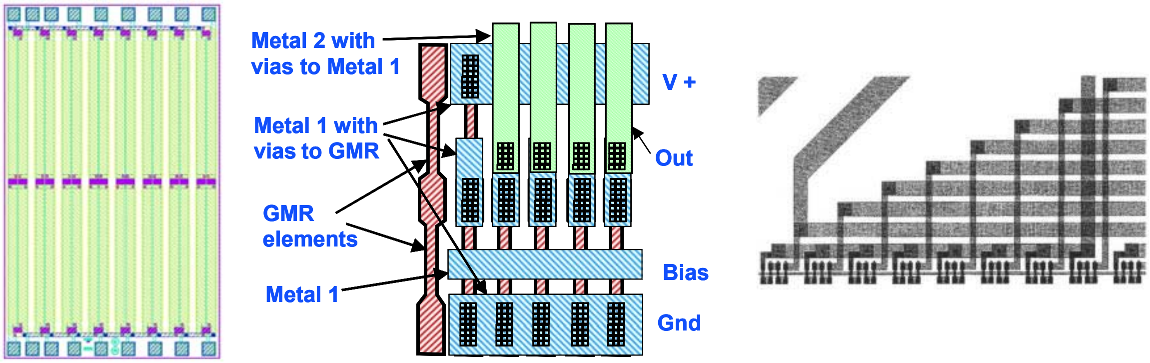
Because magnetic fields are undisturbed by and penetrate many structural components, magnetic sensors have been proposed for remote monitoring of stresses in embedded steel reinforcements and fasteners. The magnetic properties of steel change with stress through the magnetoelastic effects. Ricken et al. used a GMR sensor and permanent magnet sources to correlate the change in permeability of a steel specimen with strain[28]. Over the range of strains measured, they showed a relatively linear response with low hysteresis.

The resistivity of aluminum changes with temperature. This change can be observed through remote eddy current measurements. By using low frequencies (100 Hz) , Shay *et al.* at JENTEK Sensors were able to determine the temperature of an aluminum plate through an intervening 6.7 mm thick aluminum plate[29]. The effect of conductivity variation in the intervening plate was compensated for by measuring its eddy current response at 10 kHz. The authors point out that with more frequencies one could map out the depth profile of temperature in the specimen. The wide bandwidth of the GMR sensor was essential to this experiment.

In another remote monitoring experiment, Siddoju *et al.* at the University of Dayton considered the remote monitoring of conductivity as an indicator of the evolution of microstructure during the heat treatment of aluminum[30]. They used specially designed GMR sensors that are stable to 200º C. The authors propose that multiple frequencies could be used to compensate for temperature induced variations in probe sensitivity or lift-off.

Array sensors

As noted earlier, one key advantage of MR sensors is that they can be batch fabricated to obtain many identical sensors. Using standard electronic component packaging, arrays of discrete MR sensors can be arranged on a printed circuit board with a spacing of 5-6 mm. For a tighter effective sensor pitch, multiple arrays can be staggered on adjacent circuit boards.



(a) (b) (c)

Fig. 10. Layouts for several linear arrays of GMR sensors. (a) An 8-element array of full bridge sensors with flux concentrators with 200 µm pitch. (b) Part of a 16 element array with half-bridge sensors on a 5 µm pitch. (c) Part of a 128 element array on a 32 µm pitch.

Kataoka *et al.* at Shinshu University made a linear array of 20 GMR sensors with 0.5 mm pitch on a polyimide film[31, 32]. The GMR sensors had a unique serpentine pattern that gave them anisotropic in-plane sensitivity. Coupled with a rotating in-plane excitation field this resulted in a non-directional response function. They successfully imaged a hole defect in steel plate using 1 Hz excitation and a single pass of the sensor array.

The highest resolution can be achieved by integrating an array of sensors on a single silicon chip. Smith et al. have implemented several designs [33-35]. The first array shown in Fig. 10 has 8 full-bridge sensors with flux concentrators on a 200 µm pitch. The length of the array is 1.6 mm. The second array is 16 elements wide with 5 µm spacing but uses only half bridges at each location. For this array, the interconnects and bonding pads for connecting signals to external circuits take up most of the die area. Integration with on-chip multiplexers would cut down on the die size as well as reduce the number of wires needed to carry signals to the controller. The largest array so far contains 128 sensors each 32 µm wide spread over a width of 4.1 mm.

In principle one could easily extent this approach to building 2-dimensional arrays of GMR sensors forming a magnetic imaging plane. Such a device could image a small area all at once with high resolution without the need to scan the sensors. To make the wiring of such an imaging device practical would require that signals be processed on-chip using integrated electronics.

7. CONCLUSIONS

The specific advantages of MR sensors already indicate their use in several NDE applications. As MR technology improves, these devices will become the sensor of choice in systems requiring high sensitivity over a broad frequency range at low cost. The prospects for high-density arrays of identical magnetoresistive sensors for rapid scanning of large areas are particularly promising. With steady improvements in sensitivity, the future looks bright for NDE with magnetoresistor sensors.

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