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EDDY-CURRENT TESTING WITH GMR MAGNETIC SENSOR ARRAYS

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ABSTRACT. The advent of GMR magnetic sensors and GMR sensor arrays with frequency-independent sensitivity offers improvements in speed, depth, and resolution in eddy-current testing. Arrays of GMR magnetic sensors allow rapid scanning of an area for defects in a single pass. The small size and low power consumption of these solid-state magnetic sensors enable the fabrication of compact arrays of sensors on circuit boards and even on-chip sensor arrays. Arrays have been fabricated with sensor spacing as small as 5 micrometers when fine resolution is required. GMR sensor elements can be deposited on active silicon substrates facilitating on-chip signal processing and multiplexing. This integration simplifies the sensor/signal-processing interface, minimizes the number of leads, and can reduce the effect of noise. This paper will discuss the technology of fabricating arrays on GMR sensors, especially on-chip arrays. Integrated sensor arrays with on-chip signal processing and multiplexing will be described. Finally, some applications of arrays to crack and corrosion detection will be discussed.

INTRODUCTION

The use of Giant Magnetoresistance (GMR) sensors and gradient sensors has been demonstrated in detection and magnetic imaging of surface cracks and features, deep cracks, and cracks initiating from edges of holes [1-7]. These studies have been done both in ferromagnetic and non-ferromagnetic materials. These solid-state magnetic sensors can 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. Single-chip arrays can be further improved by using sensors integrated with semiconductor functions on the same chip. These sensors can be deposited on active silicon substrates thereby facilitating on-chip signal processing and multiplexing. Integration reduces the effect of noise, simplifies the sensor/signal-processing interface, and minimizes the number of leads.

Arrays of very small magnetic sensors 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 sensors and Anisotropic Magnetoresisitive (AMR) sensors were not applicable to high-density arrays either due to size, power or sensitivity issues. With the advent of Giant Magnetoresistive (GMR) sensors it has become possible to manufacture such devices. The applications of these devices include magnetic biosensors, non-destructive evaluation, document validation including currency and credit cards, and magnetic imaging.

The advantages of using GMR materials in sensor arrays include the small size and low power consumption of these devices as well as their frequency-independent sensitivity and the capability of depositing them on semiconductor underlayers.

SENSOR MATERIALS AND ELEMENTS

Magnetoresistive materials exhibit a change in resistance with magnetic field. The fundamentals of GMR materials have been covered in previous papers [8,9]. A variety of GMR materials are used in sensors. Some of the more common commercial varieties use a variety of antiferromagnetically coupled multilayers. One of the first materials used in commercial GMR sensors had a saturation field of 300 Oe and GMR of 15%. Newer FeCo/Cu multilayer materials with saturation fields below 100 Oe and GMR over 10 % have also been used [10]. Figure 1 shows the MR response of various multilayer materials.

The slopes of the GMR curves in Fig. 1 are 0.04 %/G for a conventional multilayer (ML), 0.07 %/G for a low-hysteresis multilayer (LH-ML), and 0.2 %/G for a high sensitivity multilayer (OD-ML) material. In a half bridge sensor configuration, these values correspond to outputs of 0.2, 0.35, and 1.0 mV/V/G (20, 25, and 100 nV/nT @ 10 V).

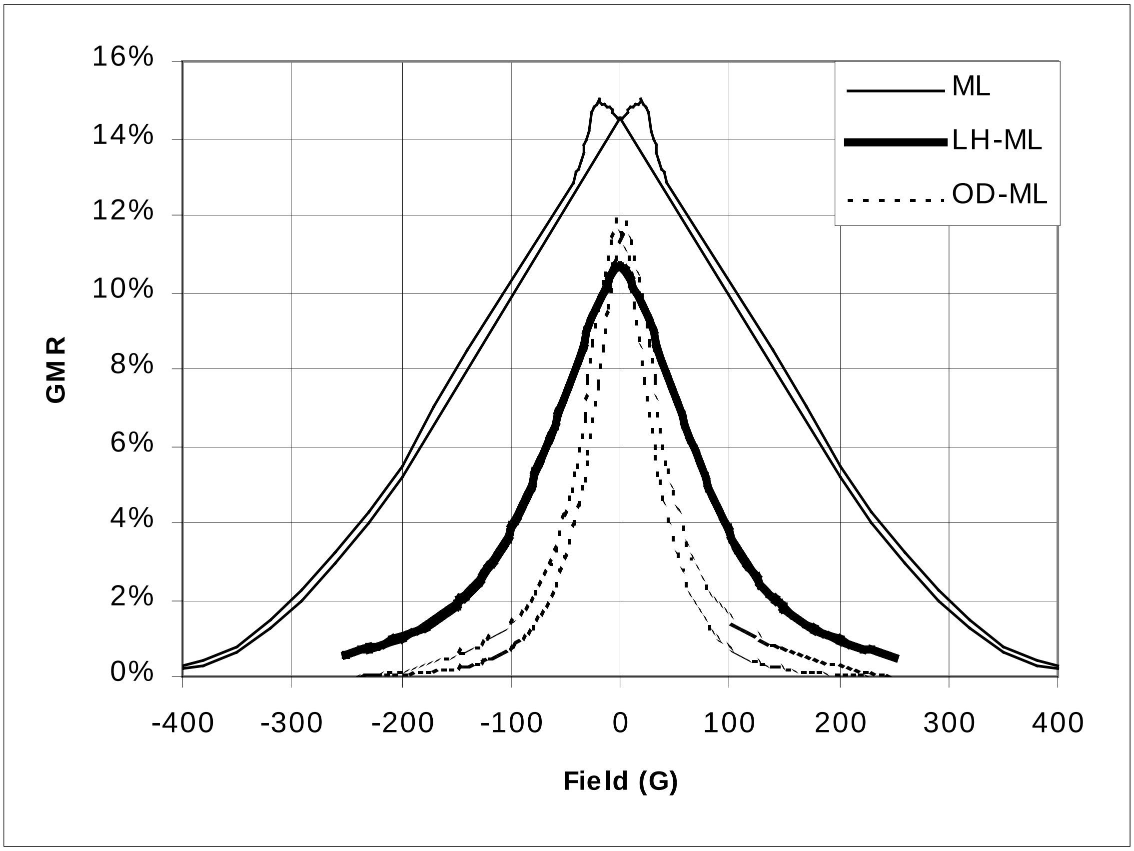

FIGURE 1. Traces of GMR *vs*. applied field for conventional multilayer (ML), low hysteresis multilayer (LH-ML), and high sensitivity multilayer (OD-ML) materials.

GMR sensor elements can be lithographically patterned to form simple resistors, half bridges, Wheatstone bridges, and even two-axis X-Y sensors. They are typically patterned into narrow stripes a few micrometers in width to provide elements with significant resistance in a small space. Their narrow width makes them sensitive only to fields along their length due to demagnetization factors.

Single resistor elements are the smallest devices and require the fewest components. However, they have poor temperature compensation and usually are combined with external resistors to form some type of bridge. Alternatively several sensing resistors can be connected in series and read out by using one differential amplifier per sensor resistor [7]. Half bridge sensors take up more area on a chip but offer some temperature compensation. Half bridges can be used as field gradient sensors if one of the resistors is some distance from the other. They can function as field sensors if one of the resistors is shielded from the applied field. Full Wheatstone bridge sensors can be fabricated where space is not as limited. Two of the resistors are protected from the applied magnetic field by magnetic shielding and serve as reference resistors in the bridge.

SENSOR ARRAYS

Sensor array design depends largely upon the specific application. Arrays include two- and three-axis sensors to measure vector fields. They can be configured as extended one-dimensional arrays of one-, two-, or three-axis sensors to survey a wide area in a single pass. Two-dimensional arrays of sensors can be left in place to survey an area without moving the array. High-resolution, one-dimensional arrays that cover a significant width require extremely small sensing elements that operate at low power levels. Arrays with large numbers of sensors often need on-board multiplexing to reduce the number of connections that need to be made to the array. Some arrays incorporate on-board coils or straps to furnish bias fields for the sensors or exciting fields for eddy-current sensing.

The design of an array with 8 sensors is shown in Fig. 2. Each sensor is a 2.5 kΩ full Wheatstone bridge. The bridges are connected in parallel with a common supply and ground. Therefore, the total resistance of the array is about 300 ohms. The total width of the array is 1.6 mm and the length is 3.1 mm. The resultant pitch of the sensors is 0.2 mm. The pads for die bonding are the rows of squares on the top and bottom. Two sensing elements for each bridge are at the center between two flux concentrators fabricated from plated soft magnetic material. The flux concentrators enhance the field in the gap between them in which the sensing resistors are located. The reference resistors are at either end of each sensor. They are protected from the applied field by being located under the flux concentrator, which acts as a shield.

An example of an array of half-bridge sensors is shown in Figure 3. This 16-element array has one sensor each 5 μm for a total width of 80 μm. The 1.5 μm GMR stripes are connected in parallel for excitation. The elements are 1.5 μm wide by 6 μm high with a similar size element above the center tap. The bottoms of the stripes are connected to a common ground connection and the tops of the half bridges are connected to a current supply. The center taps are connected to 16 separate pads on the die. A bias strap passes over the lower elements to provide a magnetic field to bias the elements.

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 number of bonding pads for the elements in the array and for lap-line monitors require the relative large 1-mm by 2-mm size of this die when compared to the 80 μm width of the array.

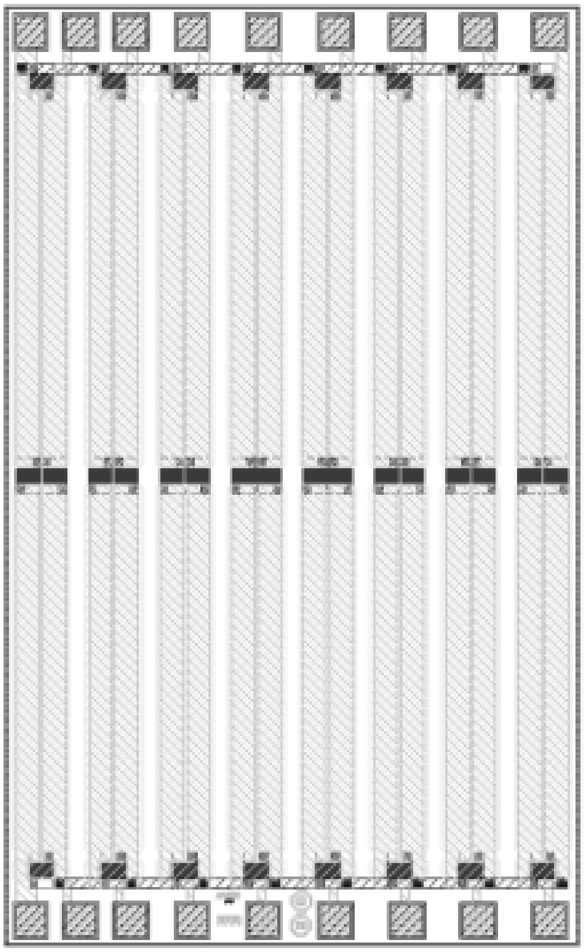

Figure 2. Arrays of Full-bridge GMR sensors including flux concentrators can be laid out on a single chip. The sensors in this array have a 200 μm pitch and share common supply and ground connections. The die size is 3.09 by 1.61 mm.

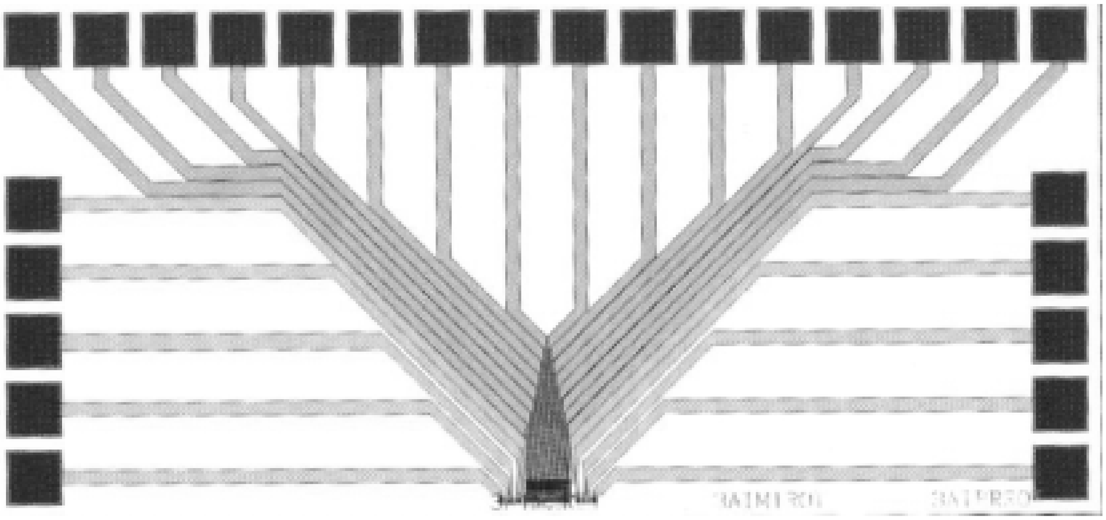

Figure 3. A 16-element array of half-bridge sensors with 5 μm spacing. Die size is 1mm x 2 mm and the total active width is 80 μm. A detailed view of the sensor elements is shown in a following figure. Lap line monitor structures border the array.

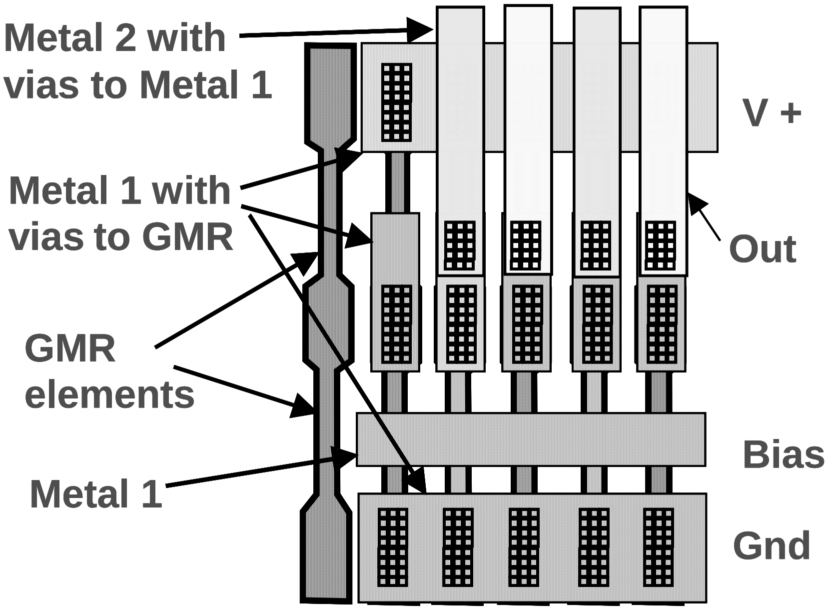

Figure 4. Part of a 16-element array of GMR half-bridge sensors with 5 μm spacing as shown in Fig 3. The first two elements have portions removed to show the three layers and their interconnections.

Wider pitch arrays of half bridges can be fabricated by using serpentine resistors instead of the single stripe resistors shown in Fig 4. Figure 5 shows the layout for a wider half-bridge array with 15 μm spacing. Serpentine resistors with 4 stripes and cross connections are used for the lower sensor element, and a single, longer stripe for the upper element. For clarity of the interconnections between layers, some of the elements are shown with metal 1 and metal 2 layers missing. A bias strap is provided to bias the elements onto the linear portion of the response curve and to provide bipolar response

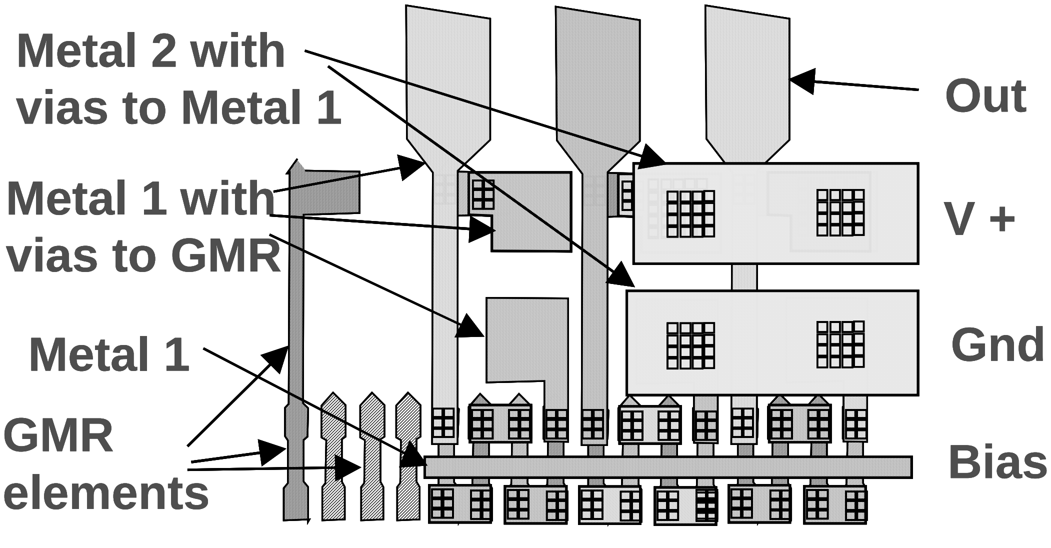

Figure 5. Four individual elements of a 16-element array of GMR half-bridge sensors with 15 μm spacing. For clarity, the first elements are shown without metal 1 and metal 2 layers and without metal 1 layers.

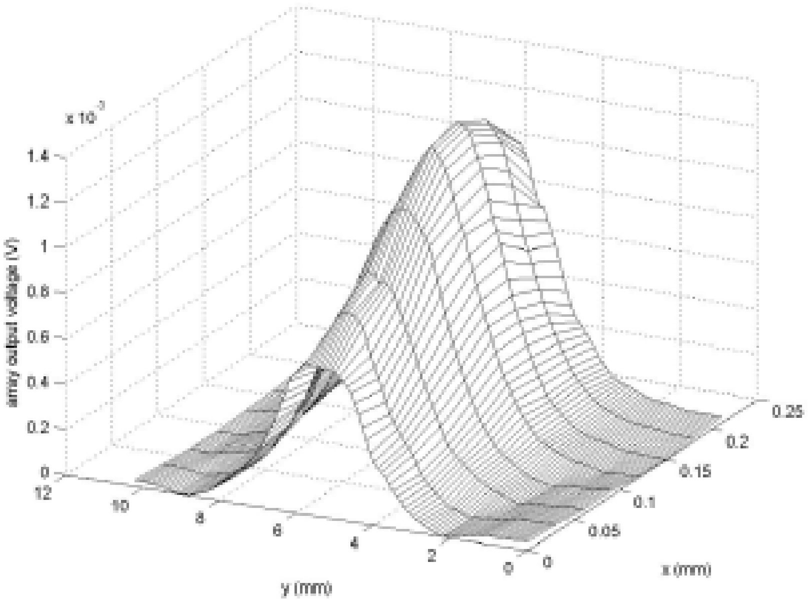

Figure 6. Response of the 8 odd elements in a 16-element array of 15 μm wide half bridges when scanned across a 0.6 mm diameter by 3 mm long 30-turn solenoid with ferromagnetic core.

The response of a 16-element half-bridge array is shown in Fig. 6. The source of the field was a 3 mm long 30-turn solenoid with a ferromagnetic core. Only the outputs from odd elements of the array are shown. Notice that the scales differ by over an order of magnitude.

APPLICATIONS OF GMR ARRAYS IN NDE

Aging aircraft must be inspected for defects that accumulate in the skin including cracks around rivet holes and corrosion between layers in multi-layer airframe skins. Eddy-current probes are typically used for this inspection, and GMR-based eddy-current probes have been shown to be an excellent choice for detecting surface cracks as well as deep cracks around fasteners [1-5]. The ability of GMR-based eddy-current probes to detect corrosion between layers was demonstrated at Albany Instruments. For this experiment, pinholes of small diameters (1.0 and 0.75 mm) of different depth were detected on the backside of an aluminum plate of thickness 1.6 mm. Two rows of holes were machined in the bottom surface of the plate to simulate corrosion-type defects. The first row consisted of four holes of 1 mm (0.04 inch) diameter, the second one of four holes of 0.75 mm diameter (0.03 inch). The depths of the holes in each row were 1 mm, 0.75 mm, 0.5 mm and 0.25 mm. The space between holes in each row was 15 mm.

The goal of the experiment was to detect these defects from the opposite side of the plate. To obtain the penetration depth and the resolution required for this type of defects, an excitation coil of mean diameter of about 2 mm was chosen. The optimum detection of defects was obtained at the frequency of 8 kHz. A schematic diagram of the eddy-current probe above the specimen during the experiment is represented in the left hand side of Fig. 7. A map of the phase of the sensor output from a two-dimensional scan of the surface is shown on the right hand side of Fig. 7.

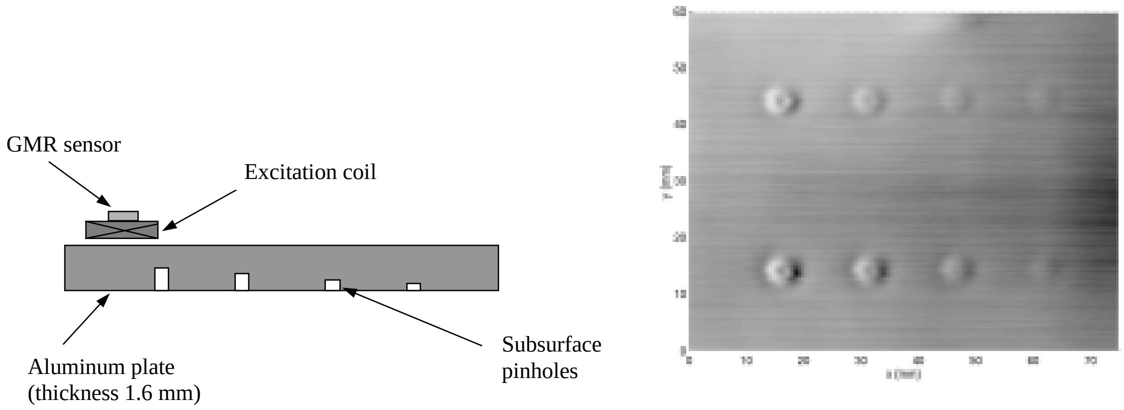

Figure 7. Left side is a schematic diagram of an eddy-current probe to detect hidden corrosion in metallic layers. Left side is a map of the phase of the sensor output from a two-dimensional scan of a specimen containing subsurface holes. The excitation frequency was 8 kHz.

Eddy-current probes have also been made using Spin Dependent Tunneling (SDT) sensors [5]. SDT sensors consist of two magnetic layers separated by an insulating layer. The tunneling current between the two magnetic layers changes as the angle between the magnetization vectors in the two layers changes in an applied field. One of the layers is pinned by an adjacent antiferromagnetic layer, and the other layer is free to follow the applied magnetic field. The high magnetoresistance (up to 60%) and the extremely low magnetic coupling between the layers result in extremely sensitive sensors [5]. An SDT-based eddy current probe was successfully tested for detecting cracks of calibrated width and depth [2]. Figure 8 shows the output of this probe. When the sensitive axis is perpendicular to the crack, a signal is observed on either side of the crack due to the asymmetry in the magnetic field from the eddy currents when they encounter the crack. In the right portion of the figure the asymmetry is detected only at the ends of the crack when the sensitive axis is parallel to the crack. The unidirectional sensitivity of sensors enables the detection of cracks at the edge of a specimen or hole. If the sensor is parallel to the edge, it will not be affected by a large edge signal but only by the signal due only to the crack. With inductive probes, the edge can produce a large signal that will mask the signal produced by a crack itself. This edge insensitivity is a large advantage in detecting cracks which initiate at edges or from fastener holes.

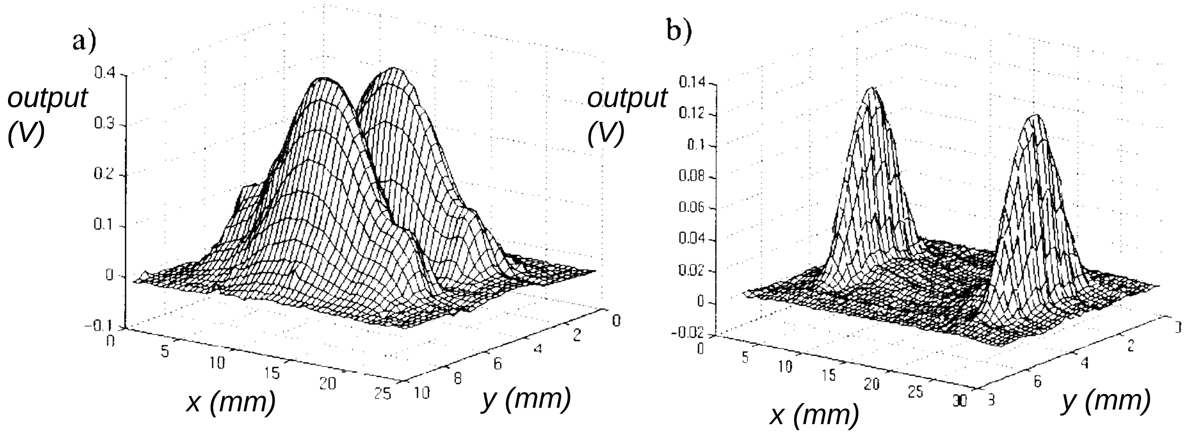

Figure 8. Two-dimensional scan using an SDT sensor in an eddy-current probe. The artificial surface crack is 15 mm long by 2 mm deep. The excitation frequency is 20 kHz. The scan on the left has the sensitive axis perpendicular to the crack while the scan on the right has the sensitive axis parallel to the crack.

CONCLUSIONS

Eddy-current probes based on GMR sensors have promise in NDE applications including interlayer corrosion, crack detection around rivet holes, and deep 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. The development of arrays of GMR sensors will facilitate much more rapid inspection over large areas.

The development GMR sensors is less than ten years old, and development of on-chip magnetic arrays is even more recent. There are technology issues to be resolved such as yield and repeatability from one element to the next. But the growing list of applications will insure the development of a variety of arrays for non-destructive applications as well as others. These on-chip magnetic sensor arrays are rooted in the same magnetic technology that is driving MRAM; therefore, rapid advances and expansion are expected in the future.

ACKNOWLEDGEMENTS

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