Spatial Detection of Ferromagnetic Wires using GMR Sensor and Based on Shape Induced Anisotropy

B. Rezaeealam* (C.A.)

Abstract: The purpose of this paper is to introduce a new technique for inter-wire spacing measurement in a wire array using Giant Magnetoresistive (GMR) sensor. Here, the wire array is exposed to an external AC uniform magnetic field in which by scanning the probe over it, the changes in magnetic field due to the shape induced anisotropy are measured. A lock-in amplifier measures the phase between the external magnetic field and the magnetic field component measured by GMR sensor. This phase signal changes abruptly by π each time the sensor passes a wire, and therefore, the distances between the wires are detected. The results verified the possibility and the performance of the proposed inter-wire spacing measurement using GMR sensor.

Keywords: Demagnetization Field, GMR Sensor, Spacing Measurement, Wire Saw.

1 Introduction

Multicrystalline silicon solar cells are manufactured from bread-loaf sized ingots of solar-grade silicon. These ingots are sliced by a multi-wire saw mechanism consisting of a single thin and extremely long stainless steel wire wound on constant-pitch wire grooves. The wire is wound over each groove to create a web consisting of 500-700 parallel wires. As shown in Fig. 1, silicon ingots are sliced with an area of 100×100 mm^2 and the latest wire saw system can achieve thickness down to 300 µm with a kerf of 200 µm utilizing a wire radius, R, of 80µm [1, 2].

Commonly, computed tomography (CT scan) using a highly collimated, low energy X-ray beam, is employed to examine the pitch of wire web and high resolution CT images for samples as large as 30 mm×100 mm are provided [1, 2]. However, the related devices are expensive and sophisticated, as they need parallel beam-formation methods [3], and also, image processing methods [4, 5].

In recent years, electromagnetic methods for eddy-current inspection have attracted increasing attention. Electromagnetic sensors, based on either Hall effect, Giant Magnetoresistance (GMR) effect [6, 7], Anisotropic Magnetoresistance (AMR) [8], or SQUID have been successfully used for the implementation of ECT. Among these, the GMR sensors offer the ease of integration with conventional semiconductor technology

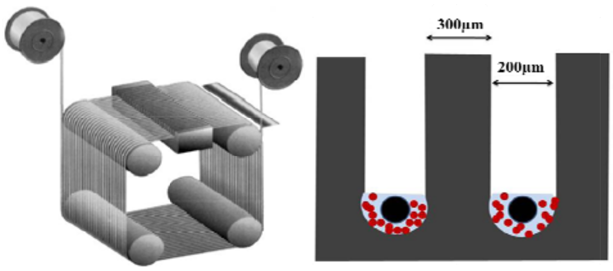

Fig. 1 An illustration of wire saw and the wafer thickness [2].

and promises smart sensors at reasonable prices with onboard signal conditioning and input regulation [9]. They have small dimensions, high sensitivity over a broad range of frequency (from hertz to megahertz domains), low noise, operate at room temperature.

The directional property of GMR sensor can be used in a difficult problem encountered in NDE, detection of edge cracks [7], contactless angle detection [10], as well as closely spaced arrays of GMR sensors enables one-pass multi-dimensional recording [11]. Also, The ability to manufacture GMR probes having small dimensions and high sensitivity (11 mV/mT) to low magnetic fields over a broad frequency range (from dc up to 1 MHz) enhances the spatial resolution of such a probe that is applicable to Eddy Current Testing (ECT) techniques. However, in many applications eddy current measurements are adversely affected by lift-off (the distance between the probe and the test sample) variations [12].

When a ferromagnetic wire is placed in a uniform magnetic field, the magnetic field is deformed as shown

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* The Author is with the Department of Electrical Engineering, Lorestan University, P.O. Box: 465, Khorramabad, Iran.
E-mail: rezaee.bh@lu.ac.ir.

in Fig. 2 due to the corresponding demagnetizing field. The proposed method to determine the distance between wires is to measure the x-component of magnetic flux density around the wires using a GMR sensor that scans in the direction transverse to the wire array. The proposed row spacing measurement in a wire array using GMR sensor is applicable to the Multi-wire slurry slicing.

2 Theoretical Derivations

Fig. 3 depicts schematically the principle of operation of the proposed method to detect the position of the wire. It is noteworthy that the direction of the external magnetic field, sensing direction and the wire axis, are perpendicular. The magnetic flux density components can be written as [13]:

$$B_r = \left(\left(\frac{\mu-\mu_0}{\mu+\mu_0}\right)\frac{a^2}{r^2}+1\right)B_0\cos\theta \tag{1}$$

$$B_\theta = \left(\left(\frac{\mu-\mu_0}{\mu+\mu_0}\right)\frac{a^2}{r^2}-1\right)B_0\sin\theta \tag{2}$$

then, the component x of the magnetic flux density along the scanning direction is derived as:

$$B_x(x) = B_r\sin\theta + B_\theta\cos\theta \tag{3}$$

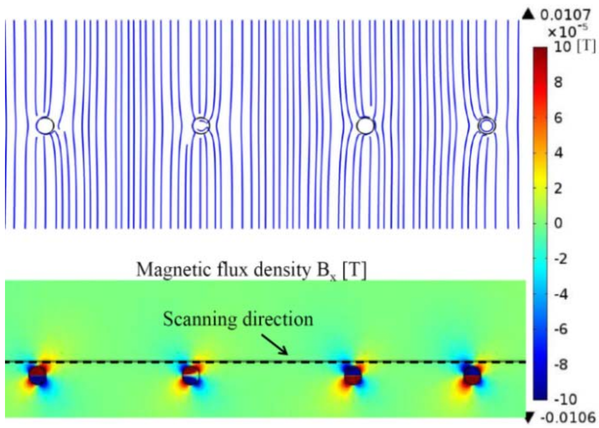

Fig. 2 Parallel wires under an applied external magnetic field.

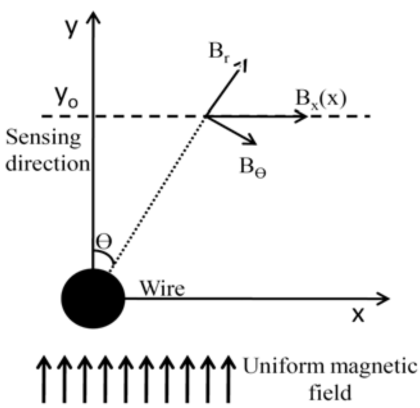

Fig. 3 Schematic illustration of the measurement method.

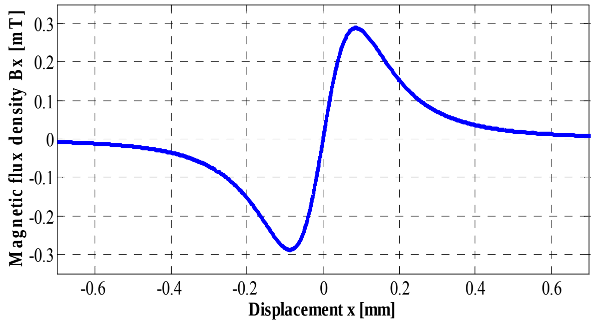

Fig. 4 x-component of magnetic flux density versus distance.

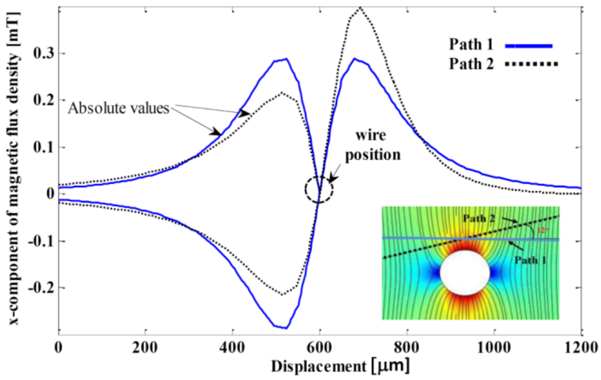

Fig. 5 x-component of magnetic flux density along different paths.

where, μ_0 and μ are the magnetic permeability of air and the wire, respectively. Putting the external magnetic flux density B_0=1 mT, frequency f=100 Hz the wire radius a=100 μm, the relative permeability of the wire μ_r=4000 and the lift-off y_0=150 μm, would result in the magnetic flux density distribution depicted in Fig. 4. It is seen that the direction of B_x is reversed by passing above the wire by which the location of the wire is detected.

In case of variations in the lift-off due to the vibration of the sensor, the magnetic flux density has been calculated using finite element method and Fig. 5 shows the x-component along a path with an inclination angle of 12° regarding the normal sensing direction. Again, the direction of B_x is reversed by passing above the wire and shows the insensitivity of the proposed method to the lift-off variation in order to detect the location of the wire.

3 The Experimental Setup and the Measurements

As shown in Fig. 6, Helmholtz coil is built in order to produce uniform fields. Typical Helmholtz coil consists of two identical circular coils of 106 turns that are placed along common axis and separated by the height equal to their radius of 12.5 cm. Uniformity of magnetic field is limited to the second order. It means that it minimizes the non-uniformity in the centre of the coils.

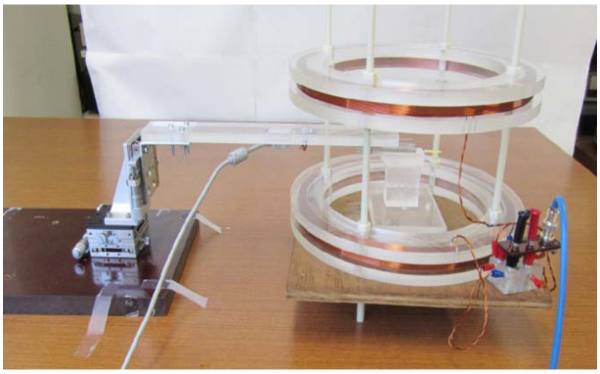

Fig. 6 Helmholtz coil.

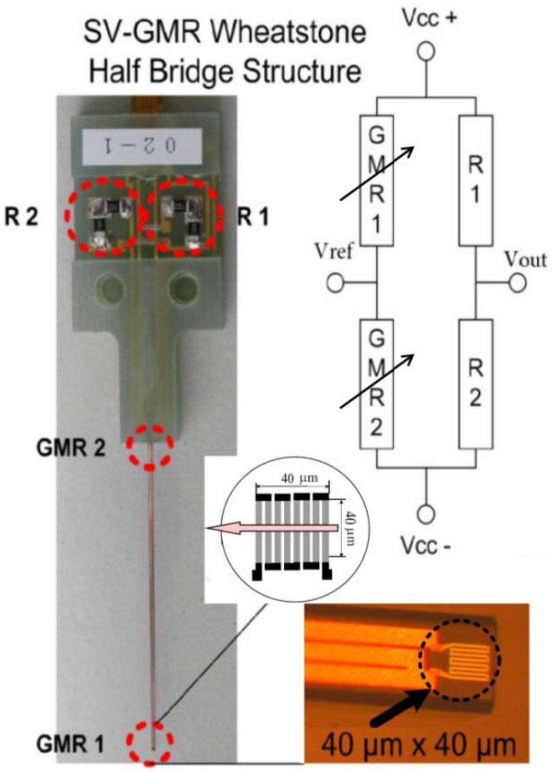

Fig. 7 SV-GMR wheatstone half bridge structure.

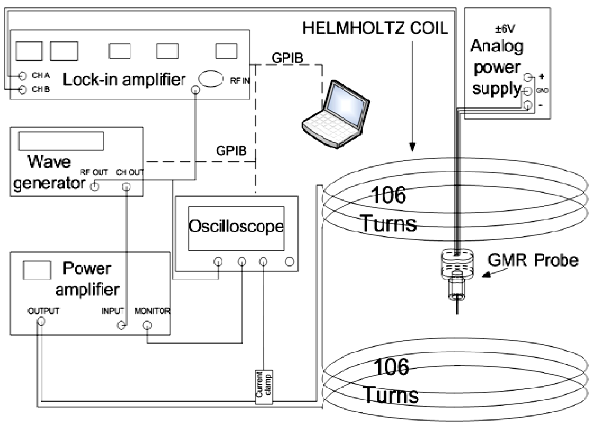

Fig. 8 Schematic illustration of the experimental set up.

As demonstrated in Fig. 7, the GMR probe has a length equal to 30 mm and the cross-section of the needle equal to 400 µm×400 µm. The needle has two GMR elements and two resistors connected into Wheatstone bridge structure. The connection of the elements creates half bridge GMR structure. One sensitive element is at the tip of the needle whereas the second one is distanced 30 mm and placed at the opposite end of the needle. This type of connection creates gradient meter which detects difference in fields rather than magnitude. This allows to precisely measure the difference between magnetic flux densities at two locations (tip and opposite side of the needle). The GMR is named as such because of the "giant" change in the resistance of the device when placed in a magnetic field. The sensitive direction of GMR elements is perpendicular to needle length as shown in Fig. 7 that allows us to detect magnetic flux densities in direction perpendicular to the needle length. This characteristic of the probe enables it to be utilized in detection of the in-phase and out of phase signal components. The designed probe has sensitive elements with the sizes 40 µm×40 µm that is built from spin valve giant magneto-resistive thin film. The needle shape allows the sensing element to approach the examined materials in a distance of few ten µm [6].

Fig. 8 shows the schematic illustration of the experimental set up. The Helmholtz coils were powered by a sinusoidal signal from the wave generator amplified by a power amplifier. The second part of the setup, the GMR probe, was supplied by an analog bipolar DC power supply. The output signal V_{out} - V_{ref} from the bridge of the GMR probe are amplified by the AD524 amplifier and connected to the lock-in amplifier. The amplitude and the phase of the output voltage from the sensor are recorded by the computer connected to the lock-in amplifier by GPIB interface.

In order to assure that hysteresis of the GMR material does not influence the measurements, the experiment with the Helmholtz coil in small AC fields was performed. Helmholtz coil was producing 0.1 mT of alternating magnetic field with the frequency 100 Hz.

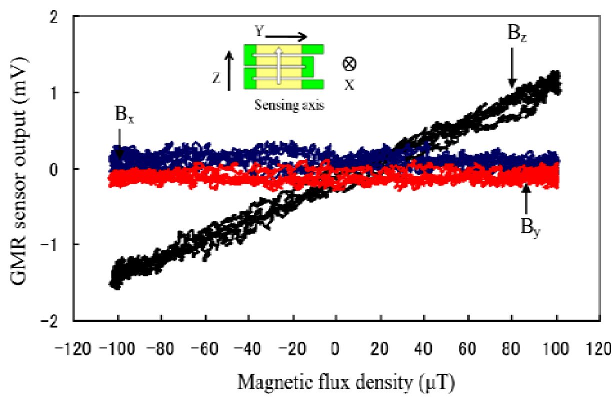

Fig. 9 Small AC characteristic of the GMR sensor.

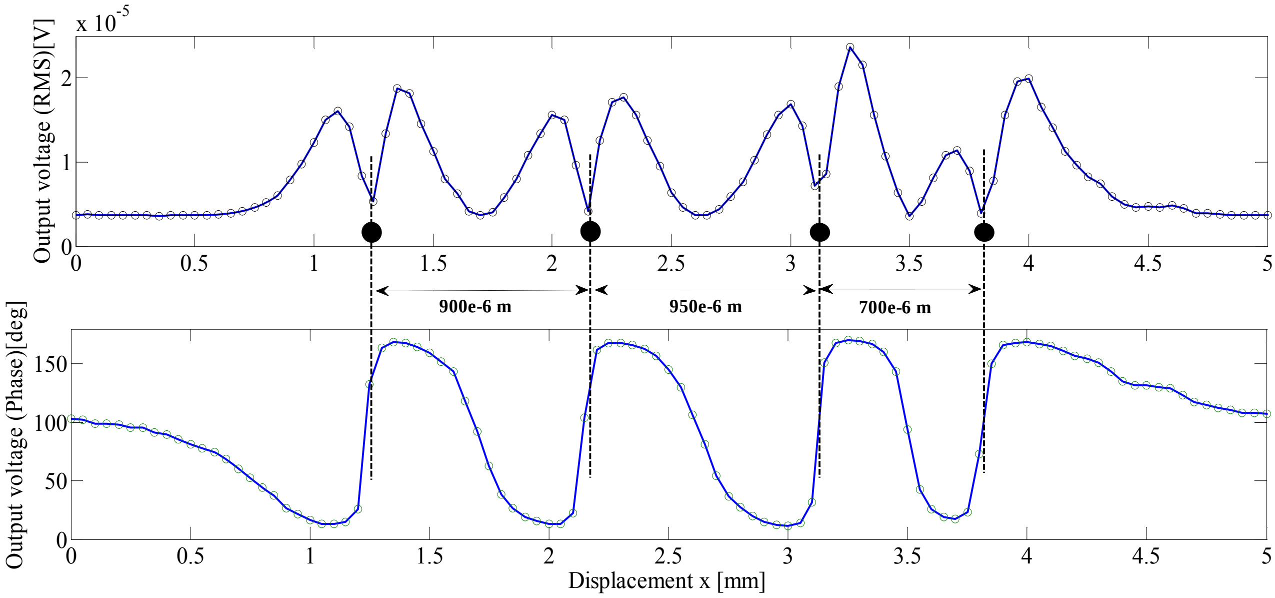

Fig. 10 The amplitudes and phases of the output signal along the scanning direction.

The tip of the needle type probe was placed in the geometrical center of the coils. The resulting output signal of the GMR element at the tip of the needle was supplied to the oscilloscope and transferred by GPIB interface to a computer. The data collected by a measurement in X, Y, and Z axes are presented in Fig. 9. It can be noticed that in X and Y axes the sensor do not react on externally applied field. In Z axis sensor linearly changes it's amplitude with the magnetic field. Hence, the sensor bridge presents high sensitivity in Z axis.

Four acupuncture needles with diameter 100 µm were placed in the center of the Helmholtz coil in which a current of 100 mA produces a uniform magnetic flux density of 0.1 mT at the frequency of 100 Hz, as the GMR element is only sensitive to AC magnetic field.

As well as, the acupuncture needles are ferromagnetic and their relatively high value of permeability causes more nonuniformity in the magnetic field due to the shape induced anisotropy in the direction transverse to the acupuncture array as shown in Fig. 2. In other words, the variation in x-component of magnetic field at the vicinity of the acupuncture needles would be higher due to the higher demagnetization field and actually this provides a direct measurement of the anisotropy caused by the acupuncture array. As a result, in this case of ferromagnetic needles, the experiments are done under the magnetic field with the low frequency of 100 Hz despite the majority of ECT techniques that employ high frequencies applied to the conducting materials. It is noteworthy that increasing the frequency demands a more powerful power supply to maintain the current of coil at 100 mA.

The lift-off distance was not measured and by eye it can be said it is about 300-500 µm. The bridge output signal V_{out}-V_{ref} was supplied to the amplifier and then to the lock-in amplifier as depicted in Fig. 8, in which the phase difference between the external magnetic field H (A/m) and the measured magnetic flux density B (T) by GMR sensor is derived, in addition to the amplitude of the output signal V_{out}-V_{ref} .

Fig. 10 shows that the phase signal changes 180^o rapidly as the tip of sensor passes an acupuncture needle and its corresponding location is detected. The inter-wire spacings are: 900, 950 and 700 µm. In the waveform of amplitude versus distance of Fig. 10, the left and right peak heights are not same, because of the proximity effect between needles.

To demonstrate clearly that the proposed method is able to measure the inter-wire spacing with reasonable accuracy, a small piece of PCB as shown in Fig. 11, was used in which the width and the pitch of the parallel conductors is 200 µm and 400 µm, respectively. After inserting the PCB in the Helmholtz coil and scanning it by GMR sensor, the corresponding phase signal was derived and shown in Fig. 12 that exhibits suitable accuracy in spatial detection of wires.

4 Conclusion

The proposed method for the inter-wire spacing measurement was successfully tested using an array of acupuncture needles that is based on the shape induced anisotropy and measuring the corresponding changes in the magnetic field using a GMR sensor. It was observed that the phase signal provided by the lock-in amplifier, changes 180^o rapidly as the tip of GMR sensor passes an acupuncture needle by which the distances between the wires in a wire saw can be measured. The proposed technique is insensitive to lift-off variation and also is able to measure the inter-wire spacing with excellent accuracy.

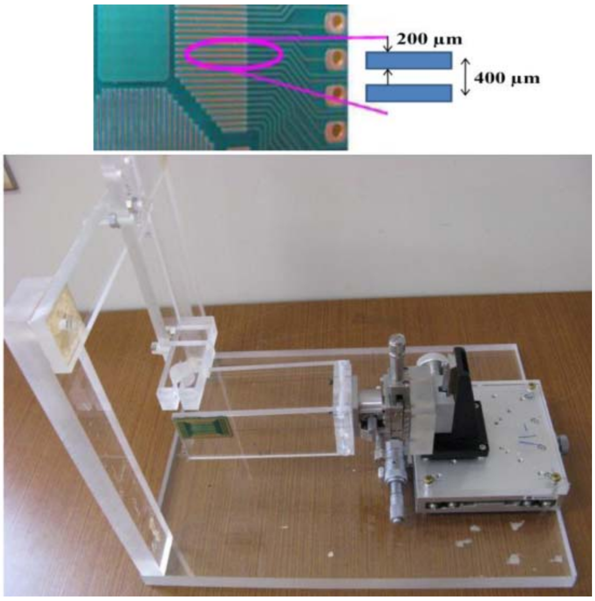

Fig. 11 Parallel conductors of the PCB.

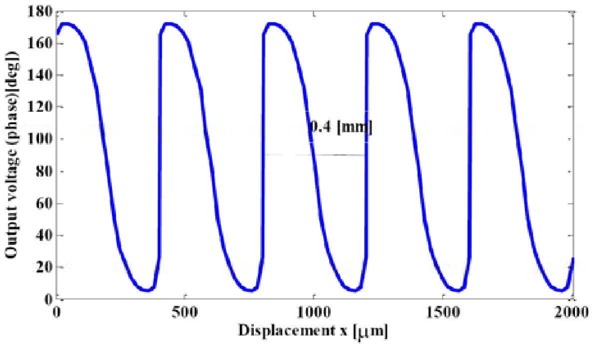

Fig. 12 The phase of the output signal along the scanning direction.

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Behrooz Rezaeealam (born in 1975) received the Ph.D. degree in electrical engineering from University of Tehran in 2005. Since 2006, he has been working as an assistant professor at the Department of Electrical Engineering, Faculty of Engineering, Lorestan University, Iran. Also, in 2011, he worked at Kanazawa University, Japan, as a postdoc researcher working on numerical modeling of magnetostrictive materials and actuators. His research interests are finite element modeling of electrical actuators, electrical motors and generators.