Sensor and Simulation Notes

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Thin Film Magnetoresistance Magnetometer

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Abstract

A thin film alloy of Ni-Fe-Co is etched such that it resembles electrically a Wheatstone bridge except that the arms of the bridge are magnetoresistive. The resistance of one arm increases and the other decreases when in the presence of a magnetic field. The primary feature of this magnetometer is its fast response time. Tests have shown that it has a flat response to alternating magnetic fields with frequencies as high as 65 MHz which was the limit of our test equipment. We have reason to believe that our present system will measure pulses with risetimes as fast as 4 nanoseconds with less than 5% error.

I. Introduction

The magnetoresistance of Ni-Fe-Co thin films lends itself to the construction of versatile magnetometers. Among the attainable features of such magnetometers are high frequency response, linearity, large dynamic range, and sensitivities which can be easily changed to detect maximum fields ranging from one to thousands of gauss. With some loss of bandwidth, much smaller fields can be measured.

II. Physical Properties

A thin film of a 73-16-11 alloy of Ni-Fe-Co is vapor deposited to a thickness of 1000-2000Å on a glass substrate maintained at 425°C. This composition was selected because, of all the materials considered, it had the largest magnetoresistance effect consistent with the other properties we desired. The film has a magnetization intensity of the order of 12,000 gauss. It can be deposited isotropically, or it can be given easy and hard axes by depositing in an external magnetic field. The resistivity of the film along the direction of magnetization is 3-4% larger than in the perpendicular direction. The angular dependence of the resistivity can be described by the equation:[1]

$$R = R_o + (\Delta R/2) \cos 2\phi \qquad (1)$$

where ϕ is the angle between the direction of magnetization and the direction of an applied current. If the field to be measured is applied perpendicular to the direction of magnetization, the angle ϕ changes, and hence so does the resistance. Since $\left|\frac{dR}{d\phi}\right|$ is a maximum when $\phi = 45°$, we shall consider the current to be at 45° with respect to the direction of magnetization when the field to be measured is zero. The direction of magnetization is obtained from the equation:[2]

$$H_x \sin \gamma - H_y \cos \gamma + H_K \sin \gamma \cos \gamma = 0 \qquad (2)$$

where H_K is the anisotropy field, the x axis is taken as the easy direction of magnetization, and γ is the angle between the direction of magnetization and the x axis.

First let us consider the case where the biasing field H_B is much larger than H_K so H_K may be neglected. Let H_s be the signal to be measured and let $H_x = H_B$ and $H_y = H_s$. Then $H_s/H_B = \tan \gamma$, and if $\phi = 45° - \gamma$,

$$R = R_o + \Delta R \cos\gamma \sin\gamma$$

or

$$R = R_o + \frac{\Delta R H_s H_B}{H_s^2 + H_B^2} \approx R_o + \Delta R \frac{H_s}{H_B}\left[1 - \left(\frac{H_s}{H_B}\right)^2 + \ldots\right] \quad (3)$$

If $H_s < 0.1 H_B$, the largest deviation from linearity is less than 1%. The above equations also hold if $H_x = H_s$ and $H_y = H_B$ with $H_K \ll H_B$.

If $|H_s| \ll |H_B + H_K|$, H_B is along the easy direction, and H_s is along the hard direction, one may write:

$$R \approx R_o + \Delta R \frac{H_s}{H_B + H_K}. \quad (4)$$

If $|H_K| < |H_B|$ and $|H_s| \ll |H_B - H_K|$, and H_B is along the hard direction with H_s along the easy direction one may write:

$$R \approx R_o + \Delta R \frac{H_s}{H_B - H_K}. \quad (5)$$

When H_B is close in magnitude to H_K, the sensitivity is significantly multiplied; however, due to inhomogeneities of the film as well as second order effects, it remains finite.

III. Magnetoresistance Bridge

When attempting to measure a dynamic magnetic field, great care must be taken to avoid false signals due to loops and the associated electric field. In order to avoid false information, an a.c. carrier much higher in frequency than the expected magnetic field is employed. This allows one to use a high pass filter and reject false signals. Since it is inconvenient to amplify or monitor an a.c. signal which is at most 2-4% modulated, the construction of a bridge is desirable. Fig. 1 shows a Wheatstone bridge intended to be used with a balanced amplifier as well as a drawing of an equivalent circuit showing resistances for the given field configuration. In the figure, $\delta = (\Delta R/2) \cos 2\phi_1 = -(\Delta R/2) \cos 2\phi_2$ where ϕ is the direction between the applied current I, and the direction of magnetization. H_K has been omitted from the figure to avoid complications. This Wheatstone bridge configuration can be used in the conventional manner by measuring the voltage difference $\frac{V\delta}{R_o}$ for a given d.c. voltage V provided there are no loop or pickup problems, or one can employ an a.c. carrier which will then be amplitude modulated by the bridge. If one uses an a.c. carrier with a balanced bridge, one will measure $|H|$ unless the phase is also detected. If one wished to measure H without phase detecting, it is convenient to unbalance the bridge slightly so there is about 60% to 100% maximum modulation.

At high carrier frequencies it is possible to avoid balanced input and output connections. The carrier frequency is fixed by the dimensions of the bridge but the response time to magnetic changes is unaffected. Fig. 2 shows a bridge which is designed for a 300 MHz carrier. The $\lambda/2$ line consists of copper electroplated over the film until its resistance is less than 1/2 ohm. The resistance R_o of each of the thin film resistors is 100 ohms. The film and half-wavelength line are covered with a clean glass slide and the two slides are sandwiched between ground planes. Thus, the half-wavelength line is equivalent to a center conductor in strip-line. The copper-plated half-wavelength line can be replaced by a length of coaxial cable one half-wavelength long with the outer conductor grounded. At 300 MHz, the cable length is about one foot. The purpose of the half-wavelength line is to invert the phase of the carrier signal. Note in the equivalent circuit diagram that the oscillator is connected to only one side of the film, and the film is not grounded anywhere. The film was etched in a symmetrical fashion only to prevent unbalance due to capacity at the rather large areas where connections are made. In practice no connections are made to one of the outer areas when the half-wavelength line is etched and copper-plated on the slide. This particular film was designed to appear as a 50 ohm load to the oscillator at 300 MHz.

An oscillator with an output impedance of 50 ohms is connected through a 50 ohm cable to the sensor. The shield of the cable is connected to the ground planes that sandwich the two glass slides which in turn sandwich the film and $\lambda/2$ line. The center conductor of the cable is connected to one side of the slide. Thus, there is no conduction path between the center conductor and ground, yet the sensor appears as a 50 ohm load and is matched to the cable and oscillator. The 100 ohm magnetoresistors are kept small so their length will be small compared to a 300 MHz wavelength. The center conductor of a second 50 ohm cable is then connected to the middle large area at the bottom of the slide as it is shown in Fig. 2. The shield of the cable is again connected to the ground planes which sandwich the glass slides. Again this cable is matched to the sensor since it is fed by two 100 ohm resistors effectively in parallel. Notice that the connections to the magnetoresistors and the $\lambda/2$ line are made only by the center conductors of the two cables. There is no direct current conduction path between the center conductors of the cables and the grounded shields at or through the sensor.

The instantaneous voltages shown in Figure 2 assume the same field configuration as shown in Figure 1. These voltages assume that the bridge is perfectly balanced when H_s is zero. This configuration is useful only if one wishes to obtain $|H_s|$, or if one wishes to phase detect with respect to the oscillator to find the polarity of H_s. In our system we unbalance the bridge slightly so that the resistance in one arm is $1.02\ R_o$, and the resistance of the other arm is $0.98\ R_o$. This allows us to measure the sign as well as the magnitude of H_s. The signal received from the sensor is then a 300 MHz carrier which is amplitude modulated in the presence of magnetic fields. For example, if a magnetic field $H_s \cos \omega_s t$ is applied to the sensor such that $\frac{H_s}{H_B} = 0.1$ with $|H_B| >> |H_K|$, and $\frac{\Delta R}{R_o} = 0.04$, then the resistance in one arm of the bridge is $1.02\ (R_o + \Delta R \frac{H_s}{H_B} \cos \omega_s t)$ and in the other arm the resistance is $.98\ (R_o - \Delta R \frac{H_s}{H_B} \cos \omega_s t)$. If under these conditions the 300 MHz signal into the sensor is $V \cos \omega_o t$, the output of the sensor will be $(.02 + \frac{\Delta R}{R_o} \frac{H_s}{H_B} \cos \omega_s t)\ V \cos \omega_o t$ or $.02V\ (1 + 0.2 \cos \omega_s t) \cos \omega_o t$ which is a 20% amplitude modulated signal. Without using a bridge the amplitude modulation would be very small and oscillator noise a problem.

In regard to dynamic range, measurements indicate that the magnetoresistors can be considered as resistors for noise calculations. The ratio of maximum signal voltage to rms thermal noise at room temperature due to the sensor itself, considering that 1 watt of noise free oscillator power is supplied, is of the order of $10^8/\sqrt{\Delta f}$ where Δf is the bandwidth. Temperature variations are generally not critical provided the magnetoresistors are at the same temperature. Our first sensors have been stored for six months and no change is noticed in their characteristics.

IV. Our Present System

The system which has been tested and is being subjected to further tests is described here. A 300 MHz oscillator followed by a band-pass filter centered at 300 MHz and a common mode rejector supplies the carrier frequency to the sensor through a 50 ohm cable. A second 50 ohm cable carries the amplitude modulated signal from the sensor through a common mode rejector and high pass filter to an instrument package. The instrument package consists of a 200-400 MHz band pass amplifier, a detector, automatic gain control, and a video amplifier. This system was designed to measure pulses with frequency components between 1 kHz and 100 MHz. The automatic gain control has a 20 db range and a one second time constant. The purpose of the automatic gain control is to compensate for differences in cable attenuation due to bends, temperature, etc. The automatic gain control maintains a constant nominal carrier level and, because of its long time constant, it does not interfere with the accuracy of the magnetometer. Thus the sensor can be calibrated in one location and fields can be measured in another without fear of error due to different cable attenuations.

Care is taken that the two 50 ohm cables do not form a loop. They are enclosed in a shield or, if this is not practical, the oscillator is supplied by a battery or power supply which is isolated from the instrument package at all frequencies.

V. Results of Tests

We were able to prove that this system was flat in its response to alternating magnetic fields as high in frequency as 65 MHz which was the limit of our test equipment. In spite of 40 db loss in cables, the signal to noise ratio is 100:1, with a 100 MHz signal bandwidth. Reproducibility over a period of weeks is within 2%. Accuracy is within 5% over the total bandwidth. The rise time of this system is thought to be 4 nanoseconds although this has not yet been verified. Pulses with 10 nanosecond rise times have been measured successfully. The limiting factor of this system is the 300 MHz carrier frequency and the electronics involved. The sensitivity of our system can be changed to detect signals ranging from 1 gauss to thousands of gauss simply by changing the permanent magnet which provides H_B. Signals smaller than 1 gauss can be measured provided the bandwidth is sufficiently limited, or a lower signal to noise ratio is acceptable. In other systems we have successfully used carrier frequencies as high as 10 GHz. It is expected that the response of magnetoresistors to magnetic fields with frequencies near 300 MHz will not be flat if H_B is near one gauss since ferromagnetic resonance occurs under these conditions. The equation for resonance is $\omega = \gamma\sqrt{B\ (H_B \pm H_K)}$.

It should also be mentioned that this type of magnetometer can be used in reverse. For example, one might apply a known alternating magnetic field as H_s, and measure an unknown static field H_B. Since the electronics associated with such a device could have a very narrow bandwidth, the range of the device could be quite large.

References

[1]J. P. Jan, Solid State Physics, edited by F. Seitz and D. Turnbull (Academic Press, New York, 1963), Vol. 5, p. 15.

[2]E.W. Pugh, Physics of Thin Films, edited by G. Hass (Academic Press, New York and London, 1963), Vol. 1, p. 300.

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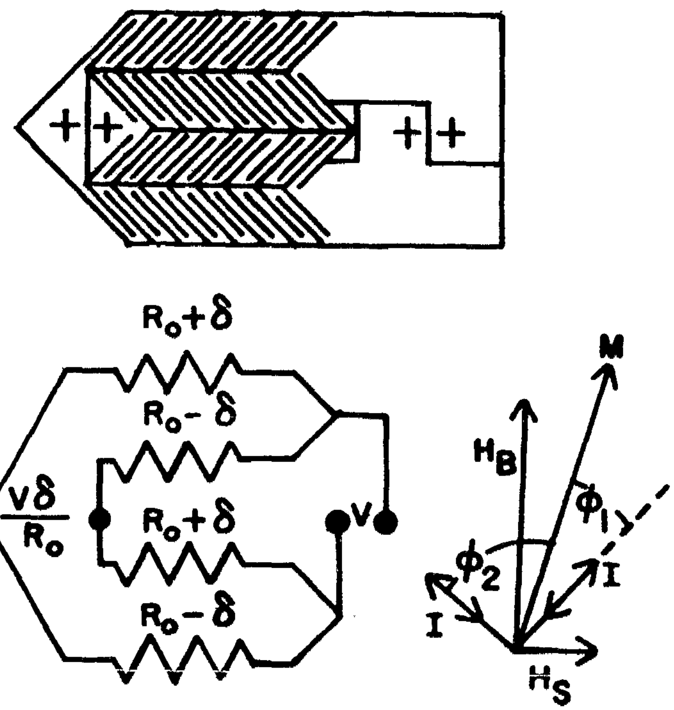

Figure 1. Pattern of Wheatstone bridge used to etch film with an equivalent circuit showing resistances for the given field configuration. The black lines on the pattern refer to locations where the film is etched away. The crosses correspond to lead connections, or to dots on the equivalent circuit.

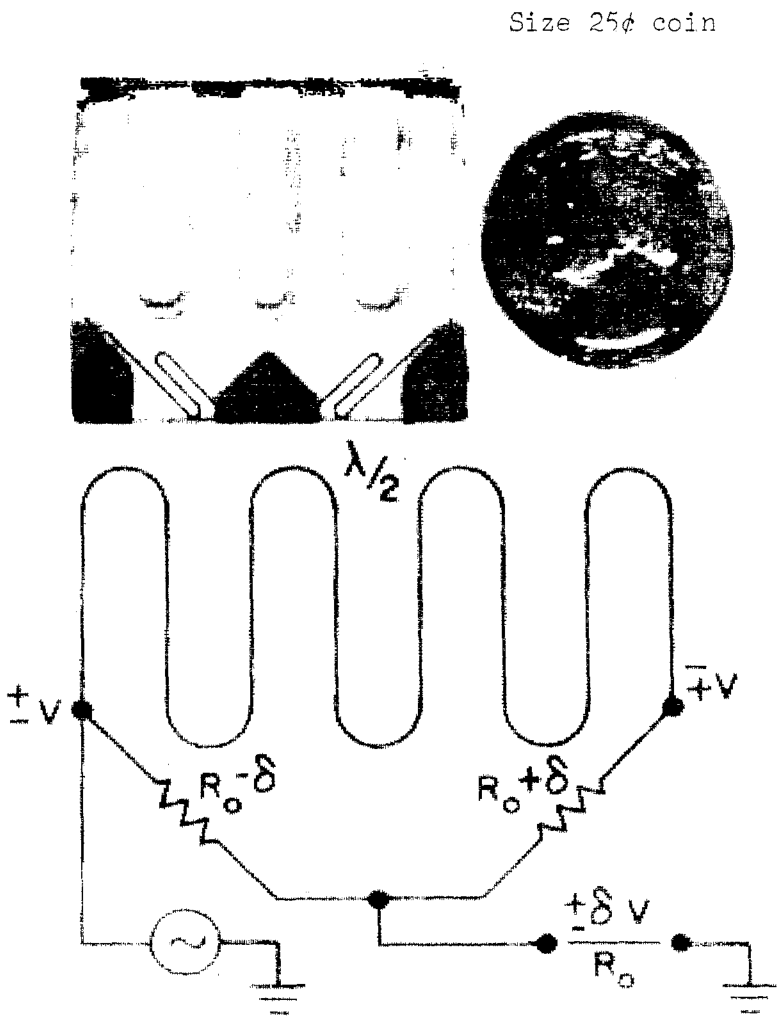

Figure 2. Photo and equivalent circuit of a bridge which needs only two connections and operates with a 300 MHz carrier.