Spin-valve GMR Sensor with Improved Ferrite core Exciter for Conductive Microbead Detection by Eddy-current Testing Technique

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This paper describes the detection of conductive microbead by spin-valve giant magnetoresistance (SV-GMR) with ferrite core exciter base on eddy-current testing (ECT) technique. The single and row conductive microbead were detected by the proposed ECT probe. The six microbeads were 125, 150, 200, 250, 300 and 360 μm radiuses. The three model of single row was slightly pitched in each row with range from 400 to 1000 μm. The analytical methods were calculated that confirmed the experimental result. The comparison of reference and proposed ECT probe signal variation with signal to noise ratio were expressed. The experimental results show that the proposed ECT can clearly detect both single and row conductive microbead position.

Key words: spin-valve giant magnetoresistance, eddy-current testing, conductive microbead, ferrite core

1. Introduction

The utilization of eddy-current testing (ECT) technique has many advantages as non-destructive testing (NDT) techniques because it is an effective way of crack detection of specimen and inexpensive. The spin-valve giant magnetoresistance (SV-GMR) has advantages such as high-sensitivity to low magnetic field over broad range of frequency and high-spatial resolution. In recent year, the ECT has been successfully applied to detection of flaw on printed circuit board (PCB). In the previous work, we reported that the ECT probe had been applied to detect the conductive microbead of both single and array.

In order to increase signal to noise ratio and enlarge signal obtained by GMR signal, the proposed ECT probe has been developed. In this paper, the eddy-current density was calculated analytically to verify the experimental result. The proposed ECT probe has been fabricated to increase the magnetic flux that is generated by exciter with the ferrite core. The positions of single microbead and a row of conductive microbeads were detected precisely by this technique.

2. Proposed ECT probe

2.1 Proposed probe structure

The proposed ECT probe consists of the SV-GMR as a sensor and an exciter as shown in Fig.1. The copper wire of 0.2 mm diameter was used for making coils and the number of turns was four turns. The copper wire was wound on the ferrite core with squares of 4 mm length. The upper and lower was connected in series. The distance between upper and lower had four mm. The conductive microbead was laid on the mid of upper and lower coil. Sensing axis of the SV-GMR sensor is parallel to x-axis. The exciting current of 200 mA was fed to the exciter for generating the magnetic field. In this work exciting frequency of 5 MHz was used.

Several specimen arrangements were studied. In all experiments the microbead material was Pb-Sn solder. For the first experiments a single microbead was used. In the single-microbead experiments six radiuses were tested (125, 150, 200, 250, 300 and 360 μm). For the second model, the microbeads were arranged in the single row. The three microbead radiuses were used (125, 150 and 250 μm) with different pitch in the range from 400 to 1000 μm.

The SV-GMR had effective sensing area of 25x200 μm. The SV-GMR consists of four strips, divided into two groups. Each group had two strips connected in series and the two groups were connected in parallel. The sensor had a protective polymer cover of 3 μm thickness.
2.2 Principle of ECT probe

The exciting current with frequency 5 MHz was fed to the exciter. The exciter construction was chosen because it produced a reasonably homogenous and straight magnetic field which is normal to the planes of the coils. Figure 2 shows arrangement of ECT probe and microbead. The exciter generates the magnetic fields which induces eddy currents in the microbead. The eddy currents in the microbead generated a magnetic field as shown. The detection approach was to measure the z-axis component of the magnetic field generated by the microbead eddy-currents.

Figure 3 shows the flux leakage of proposed probe and reference probe calculated by finite element method (FEM). The reference probe was fabricated as the Helmholtz coil. The proposed probe can decrease the flux leakage because it used the core made with ferrite material. The magnetic flux generated by proposed probe that can be higher than reference probe. The properties of ferrite material can increase the magnetic flux for the reason that it had permeability higher than air core. For this reason, the proposed ECT probe was fabricated that improved signal for SV-GMR detecting.

2.3 SV-GMR characteristic

The SV-GMR sensor was designed to have the most sensitive direction. However, some response was also expected for magnetic fields at the right angles to this direction. To determine the sensitive direction, the sensor was placed between the Helmholtz coils, but in three different orientations: with the sensitive direction aligned with the global x-, y- and z-directions. The magnetic field for these tests was driven at 10 kHz and with strength of 2.5 mT. The SV-GMR sensor was biased with a constant current of 2.5 mA. A lock-in amplifier was used to measure the voltage difference across the terminals of the SV-GMR sensor. Figure 4 shows the response of the sensor. It is confirmed that the sensitive direction responded at 72 mV/µT and this response was greater than the response of the other two directions (15 µV/µT). The normal resistance of the SV-GMR was about 1.9 kΩ.

2.4 Magnetic field Model

Figure 5 shows a simple model for the magnetic field Bi at the sensing level height. The model assumes a uniform magnetic field B0. The eddy current density inside the microbead, as predicted by the model, is:

\[ J(r, \theta, \phi) = -j\omega\sigma\mu_0 J_1(\beta r) B_0 \sin \theta \]  

where

\[ a = \frac{r_0}{\mu_0} \left\{ \frac{1}{\mu_0} J_1(\beta r_0) \right\} \left( \frac{1}{\mu_0} + \frac{1}{\mu} \right) \]

\[ k = (-1 + j) \sqrt{\mu_0/2} \]

\( \sigma = \) conductivity of the microbead (6.8×10⁶ S/m),   
\( \mu_0 \) and \( \mu = \) permeability of air and the microbead.   
\( J_0 \) and \( J_1 = \) zero and first order Bessel function.

It will be seen from equation (1) that the eddy-current density in the microbead is directly proportional to the frequency of the exciting magnetic field.
Manipulation of Equation (1) leads to an expression for the magnetic field density $B_z$ at the measurement point at lift-off height ($d$):

$$B_z = 3b \frac{r_0 (r_0 + d)}{r^3} B_0$$

where

$$b = r_0 ^3 \frac{J_1 (kr_0)}{\mu_0 \mu} - \frac{[kr_0 J_1 (kr_0) - J_0 (kr_0)]}{[ kr_0 J_0 (kr_0) - J_1 (kr_0)]} \cdot \frac{2 \mu}{\mu_0}$$

Figure 6 presents the analytical results of magnetic field occurred from eddy-current density flowing in the microbead placed under uniform magnetic field $B_0 = 100 \mu T$ and lift-off height 162 $\mu m$. We used the equation (1) for calculating the distribution of eddy-current density in conductive microbead with 125 $\mu m$ radius. We found that the distribution of the eddy current in the microbead is expected to depend on frequency because high frequency magnetic fields tend to cause a greater proportion of surface current. Thus we expect that the measured magnetic field from the eddy current will also be a function of frequency as illustrated.

Figure 7 shows the magnetic field $B_z$ over sensing track on the microbead with 125 $\mu m$, where the SV-GMR sensor is displaced with respect to the conductive microbead. Imagine that the sensor has a fixed lift-off height ($d$) and is scanned in the $z$ direction. Equation (2) can be used to find the expected magnetic field. The maximum field strength and minimum field strength are expected as the sensor passes the radius of the microbead, that is, at $z = r$ and $z = +r$. The amplitude of the magnetic field variation will depend on the microbead radius as shown in Fig.8.

Let us now consider a row of microbeads. By scanning along several lines with different values, we may build up a 2D map of the expected field strength, shown as Fig.9. The superposition technique was used to calculate the gradient of magnetic field from equation (2). It will be seen that the microbeads appear in the map as distinct visual elements. The microbead ECT detection method, simply expressed, is based on finding the distinctive pattern of “dark” and “light” caused by a microbead in such a magnetic map.

3. Recognition of conductive microbead

3.1 Investigation of single conductive microbead

The single microbeads with six radii were detected (125, 150, 200, 250, 300 and 360 $\mu m$) by both of reference and proposed ECT probe. Both of probes were
As the same power that means the probe can generate equal magnitude of magnetic flux. The signal variation of both reference and proposed ECT probe were expressed in Fig. 10. The effect of bead signal of proposed ECT probe is higher than the reference probe approximately four times because of the property of core material. Thus, the proposed exciter coil can increase flux density directly to bead.

The signals of SV-GMR obtained form the ECT probe contains not only signal of microbead detection but also noise. Figure 11 presents the signal to noise ratio (S/N) of reference and proposed ECT probe. The calculation of S/N ratio of both reference and proposed probe expresses the proposed ECT probe had low noises signal. Figure 12 presents the ECT signal and its gradient without offset that was obtained from the detection of conductive microbead with 250 μm radius at exciting frequency 5 MHz. We can define the position by considering the peak to peak of ECT signal and its gradient.

3.2 Microbead row model detection

The model of microbead row was fabricated of three radiiuses (125, 150 and 250 μm) with slightly pitch range from 400 to 1000 μm as shown in Fig. 13.

Figure 14 shows the 2-D plot of measurement: we find that the microbead position of in each model within the gradient magnetic flux density maps is distinct and can be used to estimate the microbeads positions.

4. Conclusion

The proposed ECT probe was fabricated that consists of the SV-GMR as a sensor and exciter. The proposed ECT probe can improve the signal obtained from the SV-GMR and low noise when compare with reference probe. The result of analytical method was calculated that agreed with the experimental result. This probe can be clearly verified of both single and row conductive microbead position.

This technique enables us to detect smaller bead when the SV-GMR sensor was kept as close as possible to specimen.

References


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