3. Theory

1) Multilayer GMR effect

In 1851, William Thomson discovered magnetoresistance (MR) effect whose value is usually represented by $\Delta\rho/\rho_0$, the relative change rate of resistivity, $\Delta\rho/\rho_0=(\rho_H-\rho_0)/\rho_0$, where ρ_H and ρ_0 are the resistivity of magnetic field strength at H and zero, respectively. The above expression can also be represented as $\Delta R/R_0=(R_B-R_0)/R_0$, where R_B and R_0 are the resistance of magnetic induction strength at B and zero, respectively. MR effects such as normal magnetoresistance (OMR), anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), colossal magnetoresistance (CMR), and tunneling magnetoresistance (TMR) have been discovered so far. In particular, GMR materials undertake more significant resistivity change in an external magnetic field than other MR materials, and thus they have found widespread applications.

Multilayer GMR has a layered structure consisting of alternative layers of ferromagnetic metals such as Fe, Co, and Ni and non-magnetic metals such as Cr, Cu, and Ag with a thickness of a few nanometers for each layer. The two adjacent ferromagnetic metal layers have opposite magnetic moments, so the resistance of this kind of multilayer device changes dramatically with the variation of an external magnetic field. In the absence of an external magnetic field, the material resistance is at maximum; in the presence of a strong external magnetic field, the originally antiparallel magnetic moments realign along the magnetic field direction, resulting in a minimum resistance of the device.

The multilayer GMR sensor in this apparatus adopts a Wheatstone bridge circuit and magnetic shielding technology. A layer of thick magnetic material is coated on the substrate of the sensor, which prevents external magnetic field from impacting on the GMR beneath this layer. The Wheatstone bridge circuit of the multilayer GMR sensor is shown in Figure 1, composed of four identical GMR materials with R_1 and R_3 placed on top of the magnetic material, whose resistances vary with an applied external magnetic field; while R_2 and R_4 are placed under the magnetic material, whose resistances are not affected by the external magnetic field.

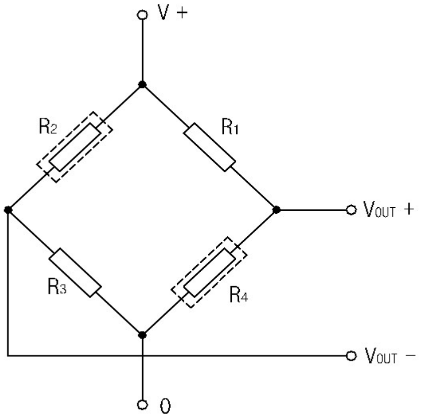

Figure 1 Wheatstone bridge circuit of GMR sensor

2) Spin valve GMR effect

The spin valve GMR effect is mainly used in information storage systems. Due to the features of low saturation field and high rate of resistance change, it can significantly reduce the volume of magnetic storage material so as to achieve high storage density.

Spin valve GMR comprises of a sensitive layer, a “fixed” layer, and an antiferromagnetic layer. The last layer freezes the magnetization direction in the “fixed” layer, while the sensitive and antiferromagnetic layers are made thin enough to reduce the resistance of the structure. The valve reacts to the external magnetic field by changing the magnetization direction in the sensitive layer relative to the “fixed” layer. When the magnetic moment of the sensitive layer is parallel to that of the antiferromagnetic layer, the device is in low resistance state; otherwise it is in high resistance state.

Similar to the multilayer GMR sensor, the spin-valve GMR sensor used in this experiment also comprises of four identical GMR materials in a Wheatstone bridge configuration, as seen in Figure 1. The resistances of R_1 and R_3 increase with the applied external magnetic field; while the resistances of R_2 and R_4 reduce with the external magnetic field.

3) AMR effect

Anisotropic magnetoresistance (AMR) effect refers to as the dependence of the resistance of a material on the direction relative to an external magnetic field, namely the parallel direction ($\rho_{\parallel}$) and perpendicular direction ($\rho_{\perp}$) of the external magnetic field. AMR device is known for small saturation magnetic field and high sensitivity, and it has been widely used in various sensors.

The AMR sensor used in this experiment consists of a one-dimensional integrated MR chip of a piece of long and thin permalloy (Fe-Ni) attached to a silicon substrate. The film resistivity $\rho(\theta)$ depends on the angle θ between the directions of electric current I and magnetization M, with the following formula

$$\rho(\theta) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp})\cos^2\theta \tag{1}$$

where $\rho_{//}$ and $\rho_{\perp}$ are the resistances of the material when the electric current I is parallel and perpendicular to magnetization M, respectively. When a DC current is applied to the alloy strip along the length direction and a magnetic field is applied to the perpendicular direction, the resistance of the alloy itself can vary significantly. Using this characteristic, the magnitude and direction of the magnetic field can be measured.

Similarly, the AMR sensor used in this experiment also comprises of four AMR devices in a Wheatstone bridge as shown in Figure 1. Since the current directions in the four AMR devices are different, the resistances of some AMR devices increase while those of other AMR devices decrease in the presence of an external magnetic field.

4) $\Delta\rho/\rho_0$ measurement principle

Since the above three types of sensors adopt a Wheatstone bridge structure with four identical magnetoresistors (R_B) only outputting differential voltages, so the magnetoresistance property of individual magnetoresistor cannot be adequately reflected. This apparatus uses the following structure to measure the ratio $\Delta\rho/\rho_0$ of different types of sensors.

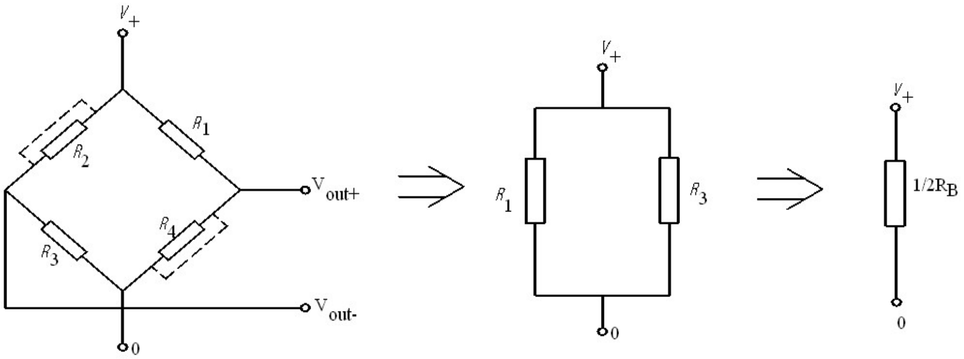

Figure 2 Structure transformation graph of Wheatstone bridge

In Figure 2, if V_+ and $V_{\text{OUT-}}$ are connected together while $V_{\text{OUT+}}$ and terminal 0 are connected together on the Wheatstone bridge, the Wheatstone bridge circuit shown on the left in Figure 2 becomes the parallel connection of R_1 and R_3 as seen in the middle of Figure 2. If each resistor has the resistance of R_B, it is equivalent to one resistor of resistance $1/2R_B$, as seen on the right in Figure 2.

In Figure 3, if resistor $1/2R_B$ is connected with a precise resistor R_a in series, by applying a constant voltage V_+ to them (5.0 V) and using a digital voltmeter to measure the voltage on R_a, the resistance property of the magnetoresistor in the Wheatstone bridge can be acquired.

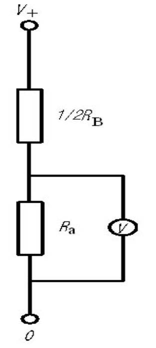

Figure 3 Schematic of measuring resistance property of magnetoresistor

In Figure 3, we have

$$\frac{V_+ - V}{V} = \frac{R_B/2}{R_a} \tag{2}$$

where V is the readout of the digital voltmeter, then we have

$$R_B = \frac{2R_a(V_+ - V)}{V} \tag{3}$$

When the magnetic field is zero, we have

$$R_0 = \frac{2R_a(V_+ - V_0)}{V_0} \tag{4}$$

where R_0 and V_0 are the resistance of magnetoresistor R_B and the readout of the voltmeter, respectively, in the absence of a magnetic field (zero magnetic field). We have

$$\frac{R_B}{R_0} = \frac{V_0(V_+ - V)}{V(V_+ - V_0)} \tag{5}$$

$$\frac{R_B - R_0}{R_0} = \frac{V_0(V_+ - V)}{V(V_+ - V_0)} - 1 \tag{6}$$

5) Application of GMR sensors in measuring current

Giant magnetoresistance sensors are widely used and can be used to measure weak magnetic fields, angles, speeds, displacements, currents, etc. Compared with anisotropic magnetoresistance sensors, they have higher sensitivity, wider linear range, higher reliability, longer life, and more resistance to harsh environmental conditions. This experiment introduces the application of GMR sensors in measuring current.

Due to the high sensitivity of a GMR sensor, it can effectively detect the magnetic field generated by a current flowing in a wire, and further acquire the current value to be measured. As shown in Figure 4, a current carrying wire is placed below (can also be above) a GMR sensor and let the current direction be perpendicular to the sensitive axis (i.e. be parallel to the pins direction) to obtain maximum sensitivity.

A current-carrying wire will generate a circular magnetic field around the wire, and its magnetic induction intensity is proportional to the magnitude of the current. When the GMR sensor senses a magnetic field, the sensor generates a voltage output. When the current increases, the surrounding magnetic field increases, and the output of the sensor also increases; similarly, when the current decreases, both the surrounding magnetic field and the sensor output decrease. After acquiring the relationship of output voltage vs input current of a GMR sensors, i.e. the sensor is calibrated, it can be used to measure the value of a unknown current.

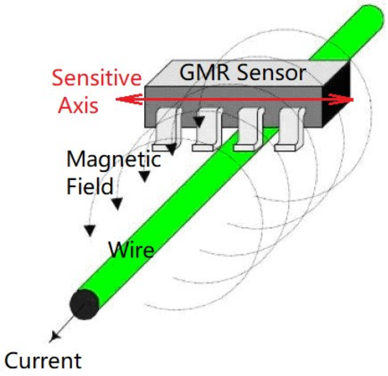

Figure 4 Schematic of measuring current using GMR sensor.