2. Theory

The change in the resistivity of a material in a magnetic field is called the magnetoresistive effect. For magnetic metals such as iron, cobalt, nickel and their alloys, if the applied magnetic field is parallel to the internal magnetization direction of the metal, its resistivity is independent of the external magnetic field; however, if the external magnetic field deviates from the internal magnetization direction, the resistivity of the metal decreases, referring to as the anisotropic magneto-resistive effect of a strong magnetic metal.

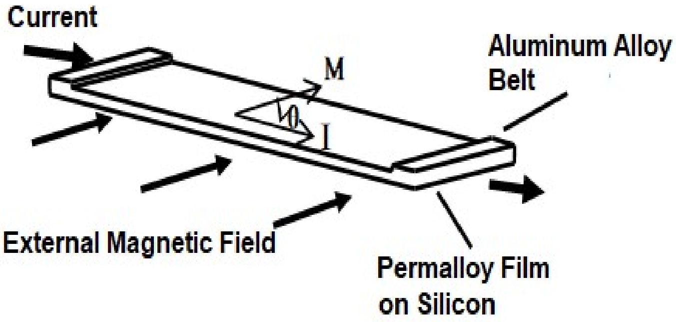

Figure 1 Schematic of magneto-resistive element

In this experiment, the magnetoresistive element of a HMC1021Z magnetoresistive sensor is made of a nickel-iron (Permalloy) thin-film deposited on a silicon wafer and patterned as a resistive strip element. In the presence of an external magnetic field, its resistivity will change. A schematic diagram is shown in Figure 1.

The resistivity $\rho(\theta)$ of the film depends on the angle θ between the magnetization strength M and the direction of the current I, with the following relation:

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

where $\rho_{//}$ and $\rho_{\perp}$ are the resistivities of the film with current I parallel to and perpendicular to the magnetic field M, respectively.

When a DC current is applied along the longitudinal direction of the Permalloy strip while an external magnetic field is exerted perpendicularly to the direction of the current, the resistivity of the alloy strip will have a notable change. From the resistivity change amount of the alloy strip, the strength and direction of the external magnetic field can be derived. There are two Aluminum belts fabricated on the two ends of the silicon wafer. One is used to set or reset the sensor (the “Reset” button) if a strong magnetic field is applied to the sensor, causing domain saturation; the other is used to generate a biased magnetic field (the “Reverse” switch) for compensating the effect of a weak magnetic field as otherwise the resistivity of the film would vary quadratically with the magnetic strength rather than a linear relationship as required.

The HMC1021Z magnetoresistive sensor is a unilaterally encapsulated magnetic field sensor that can be used to measure the magnetic field in parallel to the pin direction. The sensor is an unbalanced bridge consisting of four Permalloy magnetoresistive elements. The output of the unbalanced bridge is connected to an integrated operational amplifier to amplify the signal. The internal structure of the sensor is shown in Figure 2.

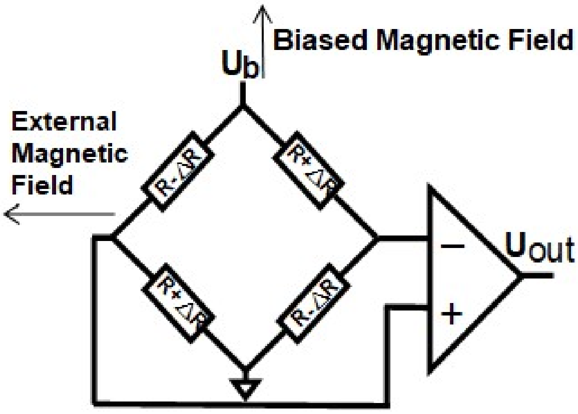

Figure 2 Internal structure of HMC1021Z magnetoresistive sensor

Due to the different current directions of the four magnetoresistive elements, the resistance value can be alternatively increased or decreased when an external magnetic field is applied. Thus, the output voltage U_{out} can be expressed as:

$$U_{out} = \left(\frac{\Delta R}{R}\right) \times U_b \tag{2}$$

For a certain working voltage (e.g. $U_b = 5.00V$), the output voltage U_{out} of the HMC1021Z magnetoresistive sensor is proportional to the magnetic strength B as:

$$U_{out} = U_0 + KB \tag{3}$$

where K is the sensitivity of the sensor; B is the magnetic field strength to be measured, and U_0 is the output voltage in the absence of a magnetic field.

Since a Helmholtz coil has a relatively large region of uniform magnetic field distribution near the center point of its axis, it is commonly used as the standard magnetic field. The magnetic field strength at the center point of the common axis of a Helmholtz coil is:

$$B = \frac{\mu_0 NI}{R} \frac{8}{5^{3/2}} \tag{4}$$

where N is the number of turns in each coil, I is the current through the coils, R is the mean radius of the coils, and μ_0 is the vacuum permeability.