Optimized Design of Plastic Package for InSb Thin-Film Magneto-Resistance Devices for Gear-Tooth Rotation Detection

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Keywords : magneto-resistance, InSb, plastic package, gear rotation detection, heat radiation coefficient

Since Sn-doped InSb single-crystal thin film shows a very large magneto-resistance effect and this effect is stable over a wide temperature range, magneto-resistance (MR) elements made from such films are suitable for devices sensing the rotation speed of spindles such as in an encoder. Examples include detecting the angular speed of spindles of various machines, wheel rotation speed, crank angles, and orientations of machine tools. Sn-doped InSb single-crystal thin films grown on GaAs (001) substrate by using molecular beam epitaxy are especially good candidates for MR devices because of their high electron mobility and small temperature dependence of film resistance. We showed that we could use these films to fabricate MR devices with good temperature properties, and that we could also fabricate high-performance gear-tooth-rotation sensors.

However, the rotation detector’s complex assembly might lead to the sensors being costly. In fact, three problems had to be solved for MR to be used to detect rotation. First, the assembly should be simple. Second, the sensor must have temperature stability. Third, the sensors must have uniform performance.

MR devices must be able to be used over a wide range of temperature and have enough reliability for the application. For such purposes, the package design should be optimized. We developed a new package design that is well-suited to rotation detection applications. In this paper, we explain the concept of the new package’s design and discuss the optimized design of gear tooth rotation detection sensors and their performance.

We developed a new package for MR devices that is optimized for gear-tooth rotation detection. Fig. 1 shows the positional relation between the package and the magnet of the new package. This package includes two MR chips.

By using this package, assembly becomes extremely easy, and positional accuracy improves, as well. One reason for this is that the accuracy of the relative position between the two MR chips depends only on the accuracy of the die bonding; thus, the deviation of the offset voltages can be minimized. The second reason is that the package has just enough space for the magnet to be inserted at the best position. The deviation of the output voltage can be reduced because of the higher accuracy of the relative positions of the magnet and MR devices.

The heat radiation coefficient of the MR devices in the newly developed package was measured and found to be 8.0 mW/°C. This value is more than twice the heat radiation coefficient of the SON package. Thus, we can apply a higher voltage to this package than to the SON at each temperature, as shown in Fig. 2.

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Fig. 1. Schematic diagram of the inner structure of package with magnet

Fig. 2. Comparison of the upper voltage limits of different packages
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This paper discusses the optimized design of the plastic package of Sn-doped InSb thin film magneto-resistance (MR) devices for gear tooth rotation detection. The newly developed package of magneto-resistance elements helps to simplify the assembly of gear-tooth rotation detectors. The properties for detecting rotation and the electrical and operational properties of the new package MR detectors were studied, including the upper limit of operation temperature.

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1. Introduction

Since Sn-doped InSb single-crystal thin film shows a very large magneto-resistance effect and this effect is stable over a wide temperature range, magneto-resistance (MR) elements made from such films are suitable for devices sensing the rotation speed of spindles such as in an encoder. Examples include detecting the angular speed of spindles of various machines, wheel rotation speed, crank angles, and orientations of machine tools(1). Sn-doped InSb single crystal thin films grown on GaAs (001) substrate by using molecular beam epitaxy are especially good candidates for MR devices because of their high electron mobility and small temperature dependence of film resistance(2). We showed that we could use these films to fabricate MR devices with good temperature properties, and that we could also fabricate high-performance gear-tooth-rotation sensors(3).

However, the rotation detector’s complex assembly might lead to the sensors being costly. In fact, three problems had to be solved for MR to be used to detect rotation. First, the assembly should be simple. Second, the sensor must have temperature stability. Third, the sensors must have uniform performance. MR devices must be able to be used over a wide range of temperature and have enough reliability for the application. For such purposes, the package design should be optimized. We developed a new package design that is well-suited to rotation detection applications. In this paper, we explain the concept of the new package's design and discuss the optimized design of gear tooth rotation detection sensors and their performance.

2. Gear Tooth Rotation Detection Sensor

The basic structure of a gear-tooth rotation sensor is shown in Fig. 1. The sensor is composed of two MR chips and a permanent magnet (bias magnet), and the permanent magnet is on the back side of the two MR chips in the sensor, so as to give a bias magnetic field perpendicular to the surface of the MR chips. The sensor is set close to the gear tooth; the gap between the gear and the sensor package surface is usually 0.1 mm to 0.5 mm. Each MR chip has four MR elements \( R_1, R_2, R_3, R_4 \), which are connected as a full bridge circuit on the chips as shown in Fig. 2 and Fig. 3. An equivalent circuit of the MR chip is shown in Fig.3. The magnetic field at the MR elements alternately varies corresponding to the approach of a gear tooth peak or valley and this causes the resistance change of the MR elements. The gear corresponding to JIS (Japan Industrial Standard) product B1701-1 (ISO/DIS 53) was tested in our experiments. The gear is denoted by module m or pitch p. The pitch is the distance between adjacent teeth of the gear and is denoted by p. The definition of a module is \( m = p / \pi \), and the unit of length is mm. (In this paper the unit of module m is neglected for simplicity). The gear used has a diameter of 102.4 mm with a tooth pitch of 2.51 mm and 128 teeth. Pitch of \( p = 0.8 \pi \) was used in our experiments. As shown in Fig.2, C and D are operating electrodes (or input electrodes), C is for operating voltage, \( V_{in} \), and D is for GND. A and B are output electrodes for the sensing signal. Two independent output signals were obtained from the output terminals A and B, as shown in Fig. 3. A DC voltage, \( V_{in} \), of 5 V was applied to operate the MR chip. The bias magnetic field was applied by magnets.

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made of SmCo with the size of W6.0 × D9.3 × T4.5 mm. The width of 6.0 mm is in the direction of the gear rotation. The remaining magnetic flux density of SmCo magnet is 0.90 T. The temperature coefficients of the remaining magnetic flux density of the SmCo magnets are −0.03%/ºC, which is very small in various permanent magnets. The relationship between the position of the gear teeth and the four MR elements is also shown in Fig. 3. Two pairs of MR elements were connected at output electrode A or B to form bridges on an MR chip. The MR elements on a chip surface were positioned corresponding to the same distance between the peak and the adjacent valley of the gear, as shown in Fig. 3. Thus, two pairs of bridges were positioned with a distance of p/4 relative to each other, so that the output signals obtained from output electrodes A and B (referred to as phases A and B below) have a phase difference of p/4, which corresponds to an electrical angle 90º, since pitch p corresponds to an electrical angle 360º. The output signal from A or B may sinusoidally vary with time corresponding to the detection of rotating gear teeth peaks and valleys. The voltage of the output signal varies with time corresponding to the detection of the rotating peaks and valleys of gear teeth at a constant rotation speed. The amplitude is defined as the difference between the maximum and minimum voltages of the output signal. High-resolution angular detection is possible, because the output signals of MR chip scarcely deviate from an ideal sine curve\(^{16}\) and the phase shift between the phase A and B is exactly 90 degrees.

The amplitude of the output voltage is one of the most important properties, and it strongly depends on the gap distance between the sensor package surface and the MR chip surface and the distance between MR elements and magnet. These distances should be minimized and kept constant in an ideal package.

Offset voltage is also an important property. Voff (A) is defined as

\[
V_{off}(A) = V(A) - \frac{V_{in}}{2} \quad \text{--------------------------- (1)}
\]

where the output voltage V(A) means the voltage of output electrodes when Vin of 5 V was applied to operate the MR device, and is measured when there is no gear tooth near the MR devices. One of the reasons why the offset voltage is not zero is that the magnetic field at the inner elements (\(R_1\) and \(R_2\)) is slightly higher than the magnetic field at the outer elements (\(R_3\) and \(R_4\)), because of the lack of uniformity of the magnetic field due to the finite size produced by the bias magnet. Such offset voltages can be minimized by using a magnet with enough large size relatively to the chip width. Moreover, the deviation of the position of the MR chips that arises from the difficulty of setting the MR chip in an ideal position during assembly results in an offset voltage deviation. Fig. 4 shows the dependence of the offset voltage on the deviation, which means the distance between the centerline of MR chip and the centerline of the magnet, in our calculation of the magnetic field in the 6.0mm and 7.0mm width of magnets as shown in Fig.6. If the both coincide, the deviation is zero. In the case of the 6.0mm width, the offset voltage with no deviation is 6.18mV and the ones with deviations of 1mm and 2mm are 8.60mV and 11.32mV, respectively. In the case of the 7.0mm width, the offset voltage is smaller, because of the better uniformity of magnetic field of the bias magnet.

3. **Package Design for Gear Tooth Rotation Detection**

We developed a new package for MR devices that is optimized for gear-tooth rotation detection. Fig. 5 shows an image of the new package, and Fig. 6 shows the positional relation between the package and the magnet. The size of the package is 16.0 × 10.5 × 6.7 mm as shown in Fig. 6. This package includes two MR chips, which are same or different. One is for phases A and B, the other is for phase Z, where Z means zero that is the origin of gear rotation. In usual gear-tooth rotation detection, the gear for phase Z has a lack of one tooth. In the case of the above two MR chips are same, the output signals obtained from output electrodes A and B (referred to as phases Za and Zb below) also have a phase difference of an electrical angle 90º.

By using this package, assembly becomes extremely easy, and positional accuracy improves, as well. One reason for this is that the accuracy of the relative position between the two MR chips depends only on the accuracy of the die bonding; thus, the deviation between phase A and Za can be reduced. The second reason is that the package has just enough space for the magnet to
be inserted at the best position. The deviation of the offset voltage can be minimized because of the higher coincidence of the centerlines of the magnet and MR chips.

Moreover, the width of the magnet is large compared with the width of the MR chips, so the offset output voltage could also be reduced as shown in Fig.4.

In addition, the back of the lead frame is bared, so the inserted magnet can be put in contact with the lead frame. The lead frame on which the MR chips are put is isolated electrically. This enables the amplitude of the output voltage to be large because the distance between the MR devices and magnet is minimized, and the heat produced in the MR devices can be efficiently radiated through the magnet because the magnet behaves as a heat sink.

Figure 7 shows the simplified assembly process. Chip-mounted lead-frame was transfer molded as shown in Fig.7(a). Eight leads were folded at the angle of 90 degree as shown in Fig.7(b). A magnet was precisely fits into the magnet holder of the package, and the package precisely fits into the cylindrical metal case, so only such insertion processes are needed to fabricate various MR device sensors using Sn-doped InSb single-crystal thin film.

Figure 8 shows an example of the measured output signals of the sensor for gear rotation detection. The gap between the top of the gear tooth and the surface of the MR chip was 0.65 mm. The frequency corresponds to the gear rotation speed and gear teeth number was 226Hz. We obtained the signals according to the gear rotation, and verified the phase shift of the two signals that are phase A and B to be almost 90 degrees.

4. Thermal Design of the Plastic Package

The upper limit of available temperature is important. In particular, we must consider the inner temperature rise caused by power consumption. Therefore, we studied the thermal properties of the MR sensor in the new package.

The power consumption is expressed by $V_{in}^2 / R_{in}$, where $V_{in}$ is input voltage and $R_{in}(T_j)$ is input resistance at the junction temperature of $T_j$, where input resistance $R_{in}$ is expresses by

$$1 / R_{in} = 1 / (R_1 + R_3) + 1 / (R_2 + R_4) \quad \ldots (2)$$

as shown in Fig 3. The junction temperature $T_{in}$ after thermal equilibrium is expressed by

$$T_j = T_a + V_{in}^2 / R_{in}(T_j) / K_t \quad \ldots (3)$$

where $T_a$ is ambient temperature and $K_t$ is a heat radiation coefficient (which is the reciprocal of thermal resistance), which is defined as a proportional coefficient of the power consumption.
temperature(5). From this formula, we can see that R_in (Tj) and Kt in the difference between the junction temperature and ambient package than to the SON at each temperature, as shown in Fig. 10.

The main reason for this result is that the area of the lead frame on which the MR chips are put is larger than the sum of the area of the two MR chips. Thus, we can apply a higher voltage to this package than to SON. It is shown in Fig. 9. This value is more than twice the heat radiation coefficient of the SON package mentioned above. We guess the radiation coefficient was measured to an accuracy of 1%, by correcting for the deviation of the fabricated devices. When the heat radiation coefficient strongly depends on the structure of the package. Figure 9 shows an example of the measured heat radiation coefficient of MR devices in a surface-mount-type SON package (D2.7 × W8.5 × T0.7 mm), which is not the new package. Eighteen devices were mounted on a printed circuit board, and the heat radiation coefficient was measured to an accuracy of 1%, by correcting for the effect of the difference in the circuit patterns. This accuracy reflected the deviation of the fabricated devices. When the heat radiation coefficient was 4.0 mW/℃, the upper limit of the inner temperature was 150℃, and the input resistance at 150℃ was 200Ω, the MR devices could be used at an ambient temperature lower than 119℃. To use the devices at a higher temperature than 119℃, the resistance would have to be raised.

The heat radiation coefficient of the MR devices in a surface-mount-type SON (Small Outline Non-leaded package) package (D2.7 × W8.5 × T0.7 mm), which is not the new package. Eighteen devices were inserted to sockets, and found to be 8.0 mW/℃.

The maximum temperature was 15℃ higher than that of the SON at 5 V. By using a package with a large heat radiation coefficient, device makers can guarantee the upper limit of temperature to be near 150℃.

5. Conclusions and Summary

We discussed the concept of our newly developed package for gear-tooth rotation sensors. The assembly process was greatly simplified, and the statistical distribution from the center value of the detection properties of mass-produced MR sensor products will be able to be reduced in comparison with the properties of conventional sensors, because the relative position between the MR chips and the coincidence with the centerlines of the chips and the bias magnet of are easily controlled. The Sn-doped InSb single-crystal thin film MR sensor has a wide operation temperature range; the upper limit of operation temperature was extended as a result of using the new package. Moreover, the rotation sensor modules showed very good temperature stability for detecting rotation through the temperature stable MR effect of the films, which are formed by molecular beam epitaxy. After the confirmation of mass productivities and reliabilities of this package, the sensors using this new package will be used for various applications such as automobile applications in the near future.

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