A giant magneto resistive (GMR) element, having a signal amplitude one order of magnitude larger than a conventional semiconductor Hall element, has been successfully applied to a revolution sensor for automotive use for the first time in the world. Featuring an original signal-processing IC and a monolithic structure, this sensor achieves a high signal-to-noise (S/N) ratio to facilitate sophisticated sensing applications such as detection of engine misfire.

Revolution sensors for automotive applications are typically used in controlling the engine, brakes and automatic transmission. Sensors employed for engine control in particular must provide high-temperature stability at temperatures above 150°C. In just ten years since the discovery of the GMR effect, with its large magnetoresistance ratio, GMR elements have been applied to magnetic heads, magnetic field sensors and other devices. However, their application to automotive sensors, which must be usable at high temperatures, has lagged behind their application to other devices. This is attributed to a problem with the long-term stability of the GMR film in a high-temperature environment. Our objective was to improve the high-temperature stability of the GMR element by annealing it beforehand under suitable conditions.

The GMR film we fabricated is a multilayer film produced by repeatedly depositing a magnetic layer, consisting mainly of Co, and a non-magnetic Cu layer. The GMR film composition, including the magnetic layer thickness and Cu layer thickness, was optimized so as to achieve a large magnetoresistance ratio and the smallest possible hysteresis.

Magnetoresistance curves measured for GMR films following annealing for ten hours at different annealing temperatures are shown in Fig. 1. Letting $R_{\text{min}} + \Delta R$ and $R_{\text{min}}$ express the maximum and minimum magnetoresistance values in the range of the measured magnetic field, the magnetoresistance ratio is $\Delta R / R_{\text{min}}$. As shown in Fig. 1, the magnetoresistance ratio increased until an annealing temperature of 250°C. However, at an annealing temperature of 300°C, not only did the magnetoresistance ratio decline sharply, the saturation magnetic field and magnetic hysteresis increased, resulting in characteristics that are not suitable for a sensing element. Judging from the desirable sensing characteristics, an annealing temperature range of 200°~250°C would be optimum. However, in consideration of the harsh temperature environment of automobiles, 250°C was selected as the annealing temperature because of the higher thermal stability that can presumably be obtained. The magnetoresistance ratio achieved following annealing at this temperature is a high 34% and hysteresis is also low, thus exhibiting excellent characteristics for a sensing element.

Fig. 2 shows the long-term high-temperature stability measured at 170°C for a GMR element that was annealed for ten hours at 250°C. The vertical axis shows the rate of change in the magnetoresistance ratio and from the smallest initial value. After 2,000 hours, the rate of change in the magnetoresistance ratio is a low 34% and hysteresis is also low, thus exhibiting excellent characteristics for a sensing element.

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change in the magnetoresistance ratio and from the smallest value was less than 1%, which is sufficiently small. These results show that the GMR element has sufficient thermal stability for use as an automotive sensor.

With the aim of reducing noise, we then examined the possibility of integrating a GMR element with a signal processing IC on a monolithic chip. To achieve a monolithic structure, it is necessary to deposit the GMR element after the IC has been fabricated, taking into account the thermal resistance of the GMR element. The issue here is how to use the phosphate-silicate glass (PSG) film, which serves as the insulator of the signal processing IC, as the GMR substrate in order to obtain excellent GMR properties. The PSG film has large surface roughness, making it unsuitable as the GMR substrate. It was found that excellent properties can be obtained by ion-beam etching (IBE) the PSG film surface for at least two minutes before depositing the GMR film. It is thought that IBE has the effect of cleaning the insulator surface that becomes dirty during the fabrication process and simultaneously smoothing large surface irregularities.

The revolution sensor for automotive application consists of the newly developed monolithic IC chip, a permanent magnet and components for protection against surge current (Fig. 3). This sensor measures the rotation of gears made of a soft magnetic material. The gear teeth made of a soft magnetic material are magnetized when they approach the permanent magnet. Because the magnetized teeth cause the GMR element to produce a magnetic field, a magnetic field that changes with gear rotation is applied to the GMR element. The changing magnetic field applied to the GMR element causes the electrical resistance of the element and also the voltage between the two terminals to vary. The voltage change is amplified and then compared by the signal-processing circuit, which converts gear rotation into a digital electrical signal, making it possible to detect the edge of the gear.

The above-mentioned characteristics of this revolution sensor were evaluated using a standard-shaped gear. Measurement accuracy was given by the deviation in the output timing of the revolution sensor relative to a high-accuracy encoder signal (reference signal) used to monitor gear rotation. As the first step, the same measurement was performed at different measurement temperatures, Ta. The gear was rotated at a speed of 7,000rpm, and the distance between the sensor and the gear was kept con-
stant at $d=1\,\text{mm}$. As shown in Fig. 4, the evaluated sensor provided excellent angle detection accuracy to within $\pm 0.26^\circ$ over a wide temperature range ($-40^\circ\text{C} \leq T_a \leq 145^\circ\text{C}$), which is one operating requirement of a revolution sensor for automotive applications.

An evaluation was then made of sensor repeatability, which is a key parameter of the misfire detection performance of a sensor intended for use in engine control. Repeatability is an index that shows the dispersion of the edge position in the sensor output signal while a gear is rotating. It is defined as the maximum rotational speed dispersion when a gear is subjected to repeated rotation tests. In order to detect engine misfire, a sensor must have sufficient accuracy to detect minute changes in rotational speed, which requires exceptionally good repeatability. Fig. 5 shows the results of repeatability measurements made at different rotational speeds under harsh conditions of $d=1.5\,\text{mm}$ and $T_a = 145^\circ\text{C}$. Nearly a flat characteristic was obtained at all rotational speeds. The timing differed slightly depending on the gear teeth, but this was caused by timing fluctuation due to sensor noise induced by external interference. This fluctuation is sufficiently small, being about one-third that of a semiconductor Hall revolution sensor. This reduction of noise has resulted from the use of a GMR element, which provides a signal amplitude that is an order of magnitude larger, and the integration of the GMR element and signal processing circuit on a monolithic chip.

The measured results show the enormous potential of the monolithic GMR sensing element for various applications, including its capability for detecting engine misfire, which was previously impossible with conventional devices.