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High sensitivity giant magnetoresistance magnetic sensor using oscillatory domain wall displacement

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A high sensitivity giant magnetoresistance (GMR) magnetic sensor has been demonstrated using the oscillatory domain wall displacing method. This sensor consists of a 30-μm-wide GMR element, CoFeB (10 nm)/Cu (2.2 nm)/CoFe (3 nm)/MnIr (10 nm), and a 100-μm-wide aluminum conducting wire placed onto the GMR element with an insulation layer between them. Domain walls in the free layer, whose easy axis is perpendicular to the length direction of GMR element, are oscillation-driven by a 140 kHz alternating magnetic field produced by an ac flowing through the aluminum conducting wire. The oscillatory wall displacement reduces the influence of wall coercivity and enables an output proportional to the external field. By applying a 1-kHz external field and separating the 1-kHz component from the amplified bridge signal using a band-pass filter, we successfully detected a magnetic field as small as 0.21 mOe (21 nT), which is much smaller than the wall coercivity of the free layer. © *2010 American Institute of Physics*. [doi:10.1063/1.3360585]

Giant magnetoresistance (GMR) magnetic field sensors[1] have been widely used in many applications such as hard-disk-drive heads,[2] linear/rotary position sensing[3,4] and biomagnetic sensing.[5–7] Compared to various other magnetic sensors, the GMR sensor has a high-frequency response, over 1 MHz, and can be easily integrated onto one chip. However, typical GMR sensors show lower field resolution than other sensors such as fluxgate and magneto-impedance sensors. Most of the spin-valve GMR sensors only utilize the rotation of free-layer magnetization to detect the external magnetic field.[5,8] For this type of sensors, a bias field is applied to saturate the free-layer magnetization along the easy axis and the external field is detected along the hard axis. On the contrary, this paper introduces a novel GMR magnetic field sensor which utilizes the oscillatory domain wall displacement of the free layer to detect the external field along the easy axis. Since the domain wall displacement is quite sensitive to the external field, and moreover, the oscillatory domain wall displacement reduces the influence of the wall coercivity and Barkhausen effect, higher sensitivity compared to the conventional GMR sensors is expected.

The sensor studied here consists of a spin-valve GMR element and an aluminum conducting wire placed on it with an insulation layer between them, as shown in Fig. 1. The GMR sensor element (30×200 μm) was microfabricated on a thermally oxidized silicon wafer (SiO_2 500 nm) using photolithography and Ar^+ ion-etching techniques, where the easy axis was perpendicular to the length direction. The GMR film stack, (Si wafer)/Ta(5 nm)/$(Co_{90}Fe_{10})_{92}B_8$(10 nm)/Cu(2.2 nm)/$Co_{90}Fe_{10}$(3 nm)/MnIr (10 nm)/Ta(2 nm), was prepared by rf magnetron sputtering at room temperature. An amorphous CoFeB free layer is preferred because of its lower coercivity. The magnetic anisotropy of the CoFeB free layer and the exchange bias between CoFe and MnIr layers were induced by applying a 200-Oe magnetic field during the deposition. An insulation layer (Al_2O_3, 200 nm thick) and a 250-nm-thick aluminum conducting wire (100 μm in width and 1200 μm in length) were micro-fabricated onto the GMR element. The resistance and the MR ratio of the GMR element were 200 Ω and 5%, respectively.

The principle of the sensor studied here is the utilization of oscillatory domain wall displacement to detect the external field. However, in the GMR element, interlayer coupling exists between the free layer and the pin layer; if no external bias field is applied, the interlayer coupling may result in the saturation of the CoFeB free layer. In order to introduce the domain walls, a bias field should be applied parallel to the easy-axis direction to cancel the interlayer coupling. Figure 1 shows the experimental arrangement. During the experiment, two independent Helmholtz coils (not shown in the figure) were used to produce a bias field (H_b) and a 1 kHz external field (H_{ex}), and both fields were parallel to the easy axis of the GMR element. First, 1-V dc bias voltage was applied to the GMR element (A, B), and a 140-kHz ac current (50 mA)

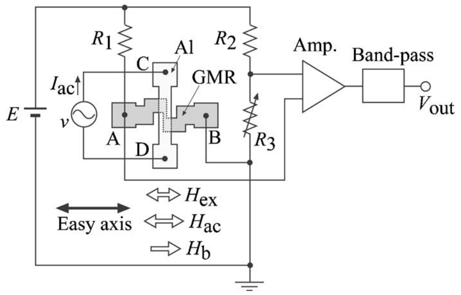

FIG. 1. Experimental configuration and signal acquisition circuit. Directions of the 140-kHz ac field (H_{ac}), 1-kHz external field (H_{ex}), and dc bias field (H_b) relative to the easy axis direction of the free layer are shown.

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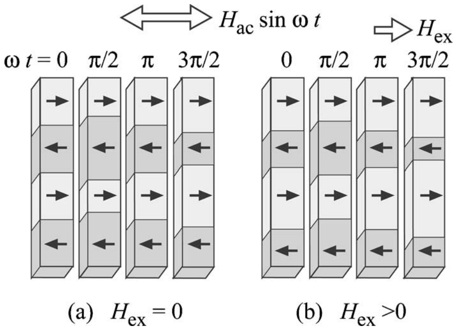

FIG. 2. Cartoon of the domain wall displacement in the CoFeB free-layer under ideal conditions. (a) External field (H_{ex}) is zero and (b) rightward H_{ex} is applied.

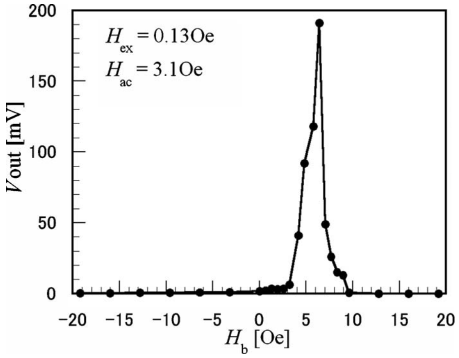

FIG. 3. Dependence of the 1-kHz signal output voltage (V_{out}) on the bias field H_b.

was transmitted through the aluminum conducting wire (C, D) to produce an alternating field H_{ac} (about 3.1 Oe), which was calculated from Ampere's law and used to drive the domain walls in the free layer. Subsequently, one of the Helmholtz coils produced a 1 kHz external field H_{ex} (0.13 Oe), which acted as the signal field to be detected. However, at this moment the domain walls in the CoFeB free layer are saturated because of the interlayer coupling mentioned above. After that, a dc bias field H_b (6.4 Oe) was applied parallel to the easy-axis direction of the GMR element (using the other Helmholtz coil) to introduce the domain walls into the CoFeB free layer. Driven by the H_{ac}, the domain walls can oscillate successively [see Fig. 2(a)], and the central positions of the oscillatory walls are modified by applying an external field (H_{ex}), as shown in Fig. 2(b). Since the domain walls are oscillation-stimulated by the H_{ac}, the central positions of the oscillatory walls can be shifted even if the external field is much smaller then the wall coercivity, and the shifting distance is proportional to the applied external field.

The output of the bridge circuit with the GMR sensor (shown in Fig. 1) was amplified by a low-noise instrumentation amplifier (IA). Since the amplified signal contained a 140-kHz component (due to the wall oscillatory displacement) and a 1-kHz signal component (due to the central position shifting of the oscillatory domain walls), the 1-kHz output signal was selectively separated using a fourth-order active band-pass filter. The root-mean-square value of the low-pass filter output was measured by a lock-in amplifier and defined as V_{out}, and the total gain for the 1 kHz signal component was 330. According to the operational principle of the sensor, if the domain walls in the CoFeB free layer are saturated, the sensor should have no response to the external field. Figure 3 shows the dependence of V_{out} on the bias field H_b. As the H_b increases from −20 to 20 Oe, the V_{out} appears in the range of 3.5 to 9 Oe and takes a maximum at $H_b = 6.4$ Oe. This result implies that the domain walls are introduced into the CoFeB free layer within this bias field range.

Figure 4 shows the field dependence of V_{out} under different H_{ac} fields. Curves A and B were measured at $H_{ac} = 3.1$ Oe ($I_{ac} = 50$ mA) and $H_{ac} = 0.93$ Oe ($I_{ac} = 15$ mA), respectively. For both measurements, a 6.4-Oe bias field (H_b) was applied. For curve B, there is no output until $H_{ex} = 2$ Oe, and V_{out} starts to increase when $H_{ex} > 2$ Oe. This nonlinear behavior implies that the H_{ac} is insufficient to drive the domain walls in the free layer since the wall coercivity of the CoFeB free layer is around 2 Oe, estimated from a minor loop of the CoFeB layer measured with the alternating gradient field magnetometer (AGM). On the other hand, in curve A and the inset of Fig. 4, a linear relationship between H_{ex} and V_{out} is displayed, which indicates that the domain walls oscillate successively under the H_{ac} of 3.1 Oe, and that the output V_{out} is proportional to the external field. According to curve A, the field sensitivity is about 2.65 mV/V/Oe, which is 8.8 times larger than the conventional integrated GMR bridge sensor[9] and 2.6 times larger than the GMR sensor used for magnetic imaging.[10] In addition, we have analyzed the frequency spectrum of the band-pass filter output, and the minimum external field H_{ex} that can be distinguished from the background noise is about 0.21 mOe. Since the domain wall displacing type sensor has higher sensitivity compared with the conventional GMR sensors, it can be used to detect smaller field changes in many low-field-detection applications, such as electronic compasses, biomagnetic detection, and precise current sensing.

In order to detect the domain wall oscillation driven by the H_{ac} more intuitively, the IA output signal was directly observed with a synchroscope. Because of the bandwidth limitation of the IA, a lower-frequency 5 kHz ac current flowed through the top aluminum conducting wire (C, D) to drive the domain walls, and the bias field (H_b) was set at 4.8

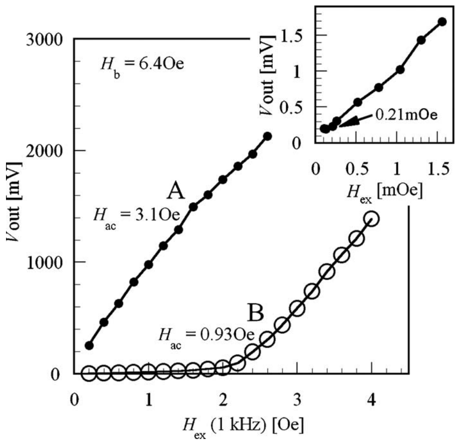

FIG. 4. Relationship between the 1-kHz external field (H_{ex}) and the output voltage under different 140-kHz ac fields (H_{ac}). Inset shows V_{out} vs small H_{ex}.

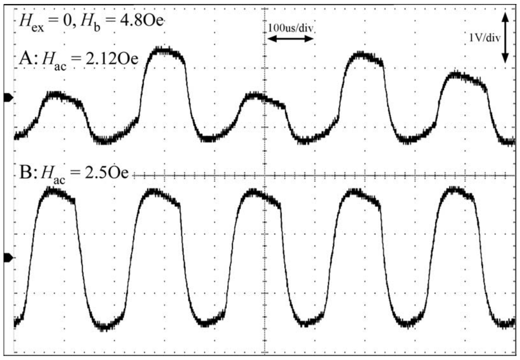

FIG. 5. Waveforms of the IA output under $H_{ac}=2.12$ Oe (waveform A) and $H_{ac}=2.5$ Oe (waveform B). The frequency of the alternating field (H_{ac}) was 5 kHz. The bias field (H_b) was 4.8 Oe; no external field (H_{ex}) was applied.

Oe. Figure 5 shows two waveforms of the IA output under $H_{ac}=2.12$ and 2.5 Oe. In waveform A, the displacement of the domain walls is erratic; this indicates that the alternating field of 2.12 Oe is not sufficient to successively drive the domain walls. By increasing the H_{ac} to 2.5 Oe, (see waveform B), the domain walls oscillate more regularly. This result also suggests that the wall coercivity of the CoFeB free layer is around 2 Oe, which is consistent with the coercivity measured with the AGM.

There are three essential conditions for utilizing a domain wall-displacing type sensor to detect the external field: (1) A proper GMR element size is necessary (here we adopted 30×200 μm GMR element, in which the domain walls can be easily formed). (2) A bias field must be applied parallel to the GMR easy-axis to cancel the inter-layer coupling between the free layer and the pin layer. (3) The domain walls in the free layer should be successively driven by an alternating field which is slightly larger then the wall coercivity. In this research, a 140-kHz ac current (50 mA) was transmitted through the aluminum conducting wire to produce an alternating field about 3.1 Oe.

By using the fabricated sensor, we carried out fundamental sensor experiments and have successfully detected a magnetic field as small as 0.21 mOe (21 nT) based on a low noise amplifier and filter circuit.

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