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Fabrication and characterization of shape anisotropy AlN/FeCoSiB magnetoelectric composite films

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Abstract

The shape anisotropy magnetoelectric (ME) composite films composed of piezoelectric AlN film and magnetostrictive FeCoSiB strips film were fabricated successfully by means of hard-mask during sputter deposition. The results demonstrated that the ME anisotropy factor K was strongly dependent on the number of FeCoSiB strips. If the number of strips is not more than eight, the ME anisotropy factor K increases slowly with increasing the strips' number. In addition, ME anisotropy factor K increases sharply when the number is more than eight. Furthermore, as the number of FeCoSiB strips increases to ten, the maximum ME anisotropy factor K reaches up to a value of 135, close to the theoretical value 175. However, by calculation, the ME anisotropy factor K will reach up to 11,357 if the FeCoSiB strips are prepared to possess the value of 1 μm in width by high precision photo-etching technology. In that case, the noise signal will be reduced to 5 nT. The shape anisotropy AlN/FeCoSiB ME composite films prepared in this work show great potential application in magnetic field detection in view of good ME anisotropy property.

Keywords: Films; Hard-mask; Magnetoelectric; Shape anisotropy; Application

1. Introduction

It is well known that geomagnetic field is on the order of 0.4–0.6 Oe and has different inclinations at different locations [1]. As Earth's natural resource and the basic physical quantity of Earth's system, geomagnetic field has considerable applications in military, industrial, medical and so on. It has been reported that the magnetoelectric (ME) sensors exhibit greater application prospects in geomagnetic field measurements compared with traditional magnetic sensors such as magnetoresistant (MR) sensors, fluxgate sensors, etc. [2–4]. In general, the high ME anisotropy is vitally necessary for ME single-axis sensors which are capable of probing the strength as well as the direction of an unknown magnetic field vector, otherwise an unacceptable aberration might be produced in weak magnetic field detection. For instance, three ME single-axis sensors orthogonal to each other can be used to detect the strength of geomagnetic field. If x, y and z denote the magnitude of three axes components (i.e., effective signal) of geomagnetic field with 50,000 nT total intensity respectively and the ME anisotropy factor is $100 < K < 1000$ which is the maximum reported up to now [5], a large noise signal as a result of insufficient ME anisotropy will be induced according to the Eq.

$$\sqrt{\left(\frac{1}{100\sim1000}\right)^2(x^2+y^2+z^2)}=\frac{50000\ \mathrm{nT}}{100\sim1000}=50\sim500\ \mathrm{nT} \tag{1}$$

Therefore, the measurement accuracy will be seriously affected unless the ME anisotropy is improved significantly or effective external compensation is employed. Different from Dong's work [5] based on stress anisotropy of piezoelectric fiber, this work investigated the ME anisotropy of AlN/FeCoSiB composite films incorporated with the shape anisotropy of FeCoSiB magnetostrictive film. According to the product property of ME composites, it is supposed that the ME anisotropy will be further improved if the piezoelectric AlN film is also prepared from shape anisotropy. Further investigation associated with the preparation of both AlN film and FeCoSiB film based on shape anisotropy will be exhibited in our future work.

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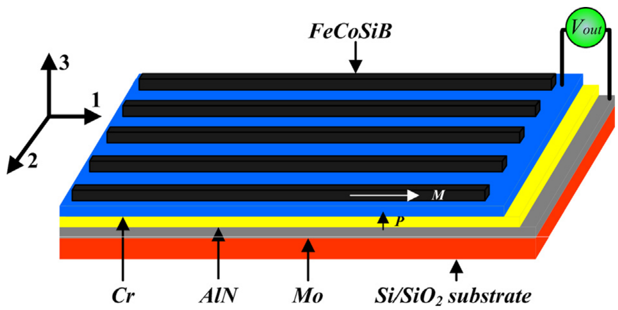

Fig. 1. Schematic illustration of the fabricated structure.

2. Experimental

The shape anisotropy AlN/FeCoSiB ME composite films were fabricated by RF magnetron sputtering (SPF-430H, ANELVA, Japan). The preparation of piezoelectric AlN film with high (002) preferred orientation had been described in detail in our previous report [6]. As the top electrode, a 300 nm Cr film was deposited on AlN film. The FeCoSiB strips with different widths in each 5×14 mm^2 area were then deposited on Cr film through hard-mask. No bias magnetic field was applied during the deposition of FeCoSiB film strips. The distance between each two strips in every region was 400 μm and the minimum width of FeCoSiB strips was 80 μm (10 strips). The schematic illustration of the fabricated structure is shown in Fig. 1. After the sputtering process was completed, the wafer was cut into 5×14 mm^2 rectangles which were further annealed in a magnetic field of 400 Oe at 350 °C for 40 min with their length parallel to direction of magnetic field. The morphology of FeCoSiB strips was observed using a Scanning Electron Microscope (SEM, Tescan Vega 3, SBH). The magnetic measurements were performed with a vibrating sample magnetometer (VSM, Lake Shore 7400) and a surface profiler (Dektak 150, Bruker, America) was used for the thickness analysis of FeCoSiB strips.

3. Results and discussions

3.1. Morphology observation and magnetic property measurement

The FeCoSiB film with 6 strips was selected to be analyzed by SEM and surface profiler, as shown in Fig. 2. It can be seen that the arrays of strips are all arranged in perfect order from SEM observation. The distance between each two strips is 400 μm and the width of strip is 260 μm, which is consistent with the result of surface profiler. Meanwhile, all the strips almost have the identical amplitude on the height of 1.5 μm. Fig. 3 shows the magnetic hysteresis loops of AlN/FeCoSiB composite films with 6 strips annealed at 350 °C by applying magnetic field parallel to the length and width of strips, respectively. The coercivity H_c along the length direction of strips is 2.3 Oe, while H_c along the width direction is 3.9 Oe. In addition, the magnetization of FeCoSiB film along length direction of strips reaches saturation at magnetic field of about 75 Oe, two times lower than that (about 150 Oe) along the width direction. This indicated that pronounced induced magnetic anisotropy has been further produced in FeCoSiB strips by means of magnetic field annealing.

3.2. Theoretical estimation

For the rectangle ferromagnetic materials, the piezomagnetic coefficient can be expressed as [7]:

$$q_e = q \Big/ \left(1 + \frac{N}{4\pi}\chi^\sigma\right) \tag{2}$$

where q_e and q are the effective and theoretical piezomagnetic coefficient, respectively; N is the demagnetization factor; χ^σ is magnetic susceptibility on the state of constant stress.

According to the basic constituent equations for quasistatic modeling of AlN/FeCoSiB ME composite films we have built in Ref. [8], the following relationship for α_E along the length and width direction can be obtained using open circuit conditions ($E_3=0$):

$$\alpha_{E,11} = \frac{v^m(s_{11,s}+s_{12,s})d_{31,p}q_{11,m}}{[v^s(s_{11,p}+s_{12,p})(s_{11,m}+s_{12,m})+v^m(s_{11,p}+s_{12,p})(s_{11,s}+s_{12,s})+v^p(s_{11,m}+s_{12,m})(s_{11,s}+s_{12,s})]\varepsilon_0\varepsilon_r} \tag{3}$$

$$\alpha_{E,12} = \frac{v^m(s_{11,s}+s_{12,s})d_{31,p}q_{12,m}}{[v^s(s_{11,p}+s_{12,p})(s_{11,m}+s_{12,m})+v^m(s_{11,p}+s_{12,p})(s_{11,s}+s_{12,s})+v^p(s_{11,m}+s_{12,m})(s_{11,s}+s_{12,s})]\varepsilon_0\varepsilon_r} \tag{4}$$

where $d_{31,p}$ is piezoelectric coefficient; $s_{11,p}/s_{12,p}$, $s_{11,m}/s_{12,m}$ and $s_{11,s}/s_{12,s}$ refer to the compliance of AlN piezoelectric layer, FeCoSiB magnetostrictive layer and Si/SiO_2 substrate; v^p, v^m and v^s denote the volume of piezoelectric, magnetostrictive phases and substrate, respectively. ε_0 and ε_r are vacuum permittivity and relative permittivity; $q_{11,m}$ and $q_{21,m}$ are defined as the piezomagnetic coefficients along the length (1-axis) and width (2-axis) direction of strips, respectively. For the magnetostrictive materials, the piezomagnetic coefficient along all direction has the relationship as follows:

$$q_{21} = \beta q_{11},\; q_{22} = \beta q_{12},\; q_{21} = q_{12} \tag{5}$$

where β is defined as the piezomagnetic factor of magnetostrictive materials with specific shape. According to Eq. (2), the χ^σ of FeCoSiB is so large that q_e can be regarded as varying inversely to N. Combining Eqs. (2) and (5), the piezomagnetic factor β can be represented as:

$$\beta \approx \sqrt{N_1/N_2} \tag{6}$$

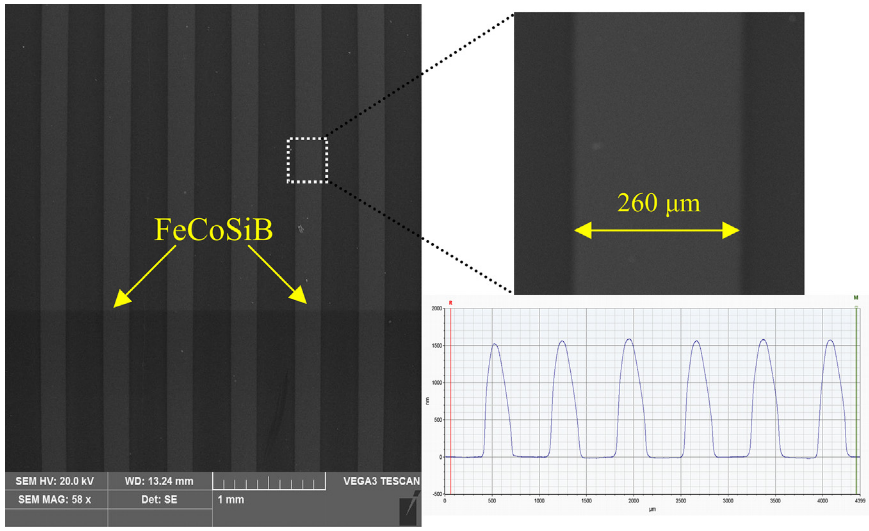

Fig. 2. The morphology and thickness of FeCoSiB film (6 strips) analyzed by SEM and surface profiler, respectively.

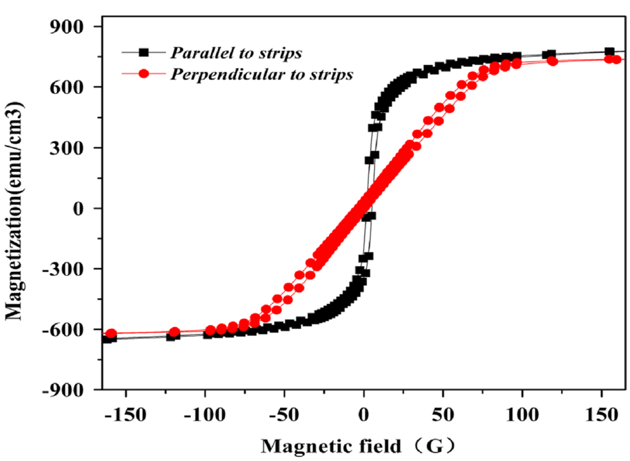

Fig. 3. M–H hysteresis loops of 350 °C annealed AlN/FeCoSiB composite films with 6 strips by applying magnetic field parallel to the length and width of strips, respectively.

Combining Eqs. (3), (4) and (6), the anisotropy factor K can be expressed as:

$$K = \frac{\alpha_{E,11}}{\alpha_{E,12}} = \frac{1}{\beta} \approx \sqrt{N_2/N_1} \tag{7}$$

For the rectangular prisms, the demagnetization factor N along the length direction (1-axis) can be given as [9]:

$$N_1 = \frac{2}{\pi}\arctan\frac{ab}{c\sqrt{a^2+b^2+c^2}} \tag{8}$$

where a, b and c denote the width (2-axis), thickness (3-axis) and length (1-axis), respectively. According to Eqs. (7) and (8), the demagnetization factor N along the length and width direction, and the anisotropy factor K of FeCoSiB film with different strips' number have been calculated, as shown in Table 1.

Table 1
The demagnetization factor N and anisotropy factor K.

Number of strips	Width of strips(μm)	N_1	N_2	K ($1/\beta$)
0	5000	2.29×10^{-5}	1.79×10^{-4}	2.79
2	1900	8.82×10^{-6}	5.19×10^{-4}	7.67
3	1100	5.17×10^{-6}	8.94×10^{-4}	13.15
4	700	3.4×10^{-6}	1.36×10^{-3}	20
5	450	2.19×10^{-6}	2.12×10^{-3}	31.11
6	260	1.27×10^{-6}	3.67×10^{-3}	53.76
7	200	9.74×10^{-7}	4.77×10^{-3}	69.98
8	160	7.79×10^{-7}	5.97×10^{-3}	87.51
9	110	5.36×10^{-7}	8.68×10^{-3}	140
10	80	3.89×10^{-7}	1.19×10^{-2}	174.9
11	60	2.92×10^{-7}	1.59×10^{-2}	233.35
12	40	1.95×10^{-7}	2.39×10^{-2}	350.09

3.3. ME anisotropy measurement

According to the current reports, there are two modes to test the ME anisotropy. The first is that both bias and ac magnetic fields are applied in the same direction while the angle between magnetic field direction and magnetization direction of sample is changing [10–12]. The second is that bias magnetic field is applied always along the magnetization direction of sample while the angle between ac magnetic field and magnetization direction of sample is changing [5]. When the ME sensors are used in actual measurement, the magnetic field to be measured can be considered to be the ac magnetic field while the bias magnetic field is applied along the magnetization direction of sample. Therefore, the second mode is adopted in this work.

To investigate the ME anisotropy, the ME voltage values are measured by changing the applied ac magnetic (H_{ac}) direction with respect to the length direction of strips. The ac magnetic field is fixed in the 1-axis direction and the sample is rotated along the 3-axis (Fig. 4). When the length direction and width direction are parallel to the magnetic field, we define $\theta=0$ and

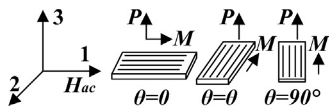

Fig. 4. Schematic illustration of ME anisotropy measurement.

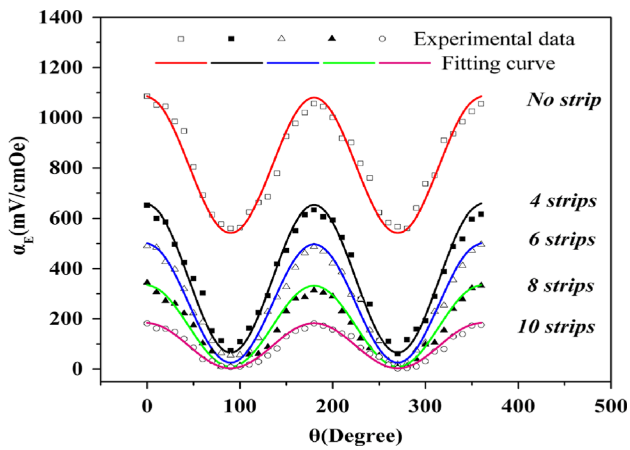

Fig. 5. Dependence of the ME coefficient (α_E) on the angle θ. The full line is the fitted curve by using Eq. (8).

$\theta = 90^\circ$, respectively. The angle variation does not affect the piezoelectric properties but changes the magnetostriction, resulting in the ME anisotropy [11]. The dependence of ME coefficient on the angle θ measured at $f = 1$ kHz and $H_{ac} = 1$ Oe was fitted by [12]

$$\alpha_E(\theta) \sim \alpha_{E,11} \cos^2(\theta) + \alpha_{E,12} \sin^2(\theta) \quad (9)$$

where $\alpha_{E,11}$ and $\alpha_{E,12}$ represent the ME voltage coefficient along length and width direction of strips, respectively.

Fig. 5 shows the dependence of the ME voltage coefficient on the angle θ. As can be seen, the experimental data are in good agreement with the fitted curve. In addition, the ME voltage coefficient decreases sharply with increasing the number of strips. For AlN/FeCoSiB composite films without strip, the ME voltage coefficient $\alpha_{E,11}$ and $\alpha_{E,12}$ are 1085 mV/cm Oe and 536.5 mV/cm Oe, respectively; while for the composite films with ten FeCoSiB strips, the ME voltage coefficient $\alpha_{E,11}$ and $\alpha_{E,12}$ reduce to 184.4 mV/cm Oe and 1.37 mV/cm Oe, respectively. It could be attributed to that the more the FeCoSiB strips in same area are, the smaller the volume of FeCoSiB film is, which gave rise to decline of magnetostrictive effect and consequently undermining the ME effect. The anisotropy factor K as a function of the number of FeCoSiB strips is shown in Fig. 6. It can be seen that the experimental data have identical tendency with the theoretical value. When the number of strips is not more than eight, the anisotropy factor increases slowly with increasing the strips' number; while anisotropy factor increases sharply with raising the number of strips when the number is more than eight. With further increasing the number of FeCoSiB strips to ten, the maximum anisotropy factor K of about 135 has been obtained, which is close to the theoretical value 175, indicating good ME anisotropy property has produced in AlN/FeCoSiB composite films. However, the fact that the larger the anisotropy factor is, the weaker the ME sensitivity will be should be considered for the application of AlN/FeCoSiB composite films prepared by hard-mask used as 3D vector magnetic field sensor. Whereas, the ME anisotropy factor K will reach up to 11,357 if the FeCoSiB strips is prepared to possess the value of 1 μm in width by high precision photo-etching technology in the case of same volume. According to Eq. (1), the noise signal will be reduced to 5 nT. In that case, the ME composites will possess both high ME sensitivity and large ME anisotropy factor.

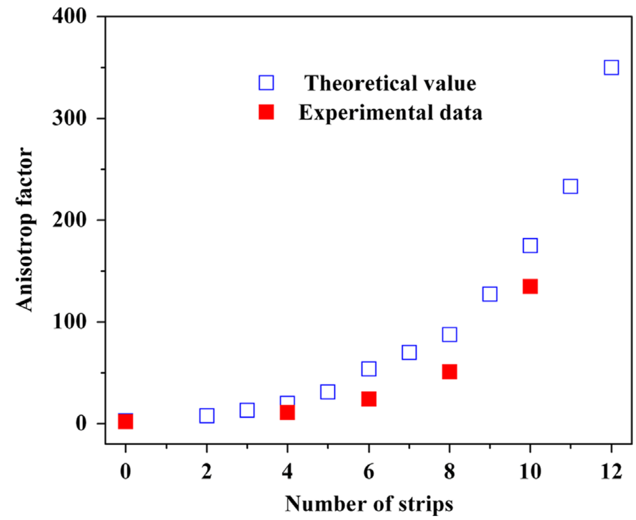

Fig. 6. The anisotropy factor as a function of the number of FeCoSiB strips.

4. Conclusions

In summary, the shape anisotropy AlN/FeCoSiB composite films have been fabricated successfully by means of hard-mask during sputtering. The results show that the ME anisotropy factor K increases gradually as the number of FeCoSiB strips increases and the experimental data of K have identical tendency with the theoretical value. When the number of FeCoSiB strips increases to ten, the maximum ME anisotropy factor K of about 135 is obtained, close to the theoretical value 175. However, the ME voltage coefficient $\alpha_{E,11}$ and $\alpha_{E,12}$ reduce to 184.4 mV/cm Oe and 1.37 mV/cm Oe from 1085 mV/cm Oe and 536.5 mV/cm Oe, respectively. The shape anisotropy AlN/FeCoSiB ME composite films prepared in this work show great potential application in magnetic field detection in view of large ME anisotropy factor.

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