Highly Sensitive Thin Film Sensor Using Coplanar Line

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A very sensitive thin film sensor was developed using a transmission line. The sensor element consisted of a coplanar line fabricated from $\text{Sr}_{33}\text{Ti}_{16}\text{O}_{51}$ (STO) film (6 μm thick), amorphous CoNbZr film (5 μm thick), and Cu/Cr film (4 $\mu\text{m}/0.2$ μm). The deposited STO film had high permittivity of around 31. The STO film enhanced the sensitivity of the sensor and a phase change of more than 100 degrees/Oe and gain of over -40 dB were achieved simultaneously. These characteristics are very similar to those of a large sensor with a bulky ceramic substrate⁶⁾.

Key words: coplanar line, thin film sensor, $\text{Sr}_{33}\text{Ti}_{16}\text{O}_{51}$ film

1. Introduction

Biomagnetic measurement such as magnetocardiography (MCG) and magneto encephalography (MEG) is applied by SQUID¹⁾²⁾ or laser-pumped magnetometer³⁾. However, these sensors are very expensive and not easily operated. On the other hand, an induction coil⁴⁾ and a fluxgate sensor⁵⁾ can be operated at room temperature; however, they are comparatively large in scale, making it difficult to integrate them in a sensor array. Highly sensitive magnetic field thin film sensors operating at room temperature are useful for biomedical applications or nondestructive evaluation. Thus, development of a thin film sensor to measure biomagnetic signals at room temperature was the aim of this study.

As previously reported, a coplanar line-type thin film sensor with a ceramic substrate ($\epsilon_r = 115$) to enhance sensitivity of phase change was developed⁶⁾ and successfully used to obtain magnetocardiograms (MCGs) at multiple points⁷⁾. The ceramic substrate with high permittivity decreases the wave length of the carrier, the phase dramatically changing when a small field is applied. However the sensor is bulky and cannot be integrated.

In the present study, we developed a thin film integrated sensor including magnetic thin film, dielectric film and conductive film. These structure can be easily developed for array sensors with the same characteristics. The goal of this study was to obtain a sensor with good characteristics (phase change > 100 degree/Oe, gain > -40 dB) for obtaining magnetocardiograms⁷⁾.

2. Experimental procedure

2.1 Coplanar line-type thin film sensor

Fig. 1 shows the structure of a coplanar line-type sensor. The sensor element consists of a coplanar line (19.8 mm in length, 0.3 mm in width, 4 μm in thickness, and having a 0.05 mm gap between conductors), $\text{Sr}_{33}\text{Ti}_{16}\text{O}_{51}$ (STO) film (6 μm in thickness), and an amorphous CoNbZr film (18.2 mm

x 1.15 mm, 5 μm in thickness), as shown in Fig. 1. The coplanar structure was fabricated by the lift-off process. The sputtering conditions are shown in Table 1. Amorphous CoNbZr film was deposited by RF sputtering on a glass substrate (25 mm x 25 mm, 1 mm in thickness). In order to induce transverse magnetic anisotropy of a few Oe, a DC field of 0.3 T was applied during annealing after film deposition. Rotational annealing was carried out at 400 °C for 2 hours, and then static annealing was conducted at 300 °C for 1 hour. The STO film was deposited by RF sputtering and annealed at 150 °C during deposition. We selected STO film as dielectric film

Fig. 1 Schematic of sensor.

Table 1 Sputtering conditions.

	CoNbZr	Sr ₃₃ Ti ₁₆ O ₅₁	Cu/Cr
Power,	200 W	200 W	200 W
pressure	20 mtorr	20 mtorr	20 mtorr
time	8 hour	12 hour	50 minutes
thickness	5 μm	6 μm	4 μm/0.2 μm

Fig. 2 Measurement setup. **Fig. 3** Photograph of coplanar line (sample A) for a measurement of permittivity of STO film. **Fig. 4** Equivalent circuit of coplanar line in open terminated.

of the coplanar line, because STO film keeps high permittivity and low loss up to GHz range. The composition of the STO film was evaluated by X-ray photoelectron spectroscopy (JEOL JPS-9010MC). The composition of the STO film was obtained about Sr₃₃Ti₁₆O₅₁. Cu and Cr film was deposited by RF sputtering. Cr film improves the contact between STO film and Cu film. The coplanar line was patterned using a lift-off. A carrier of around 2 GHz flows in the center conductor of the coplanar line. When a small magnetic field is applied to the magnetic film, permeability of the magnetic film changes, which results in the amplitude and the phase of the carrier being changed due to the skin effect and ferromagnetic resonance. The carrier current flows in the Cu conductor, not in the CoNbZr film, so the sensor is different from conventional GMI

Fig. 5 Flow chart of an evaluation of permittivity of STO film. **Fig. 6** Calculation model of coplanar line (sample A).

sensors in this respect. A magnetic field was applied in the longitudinal direction of the coplanar pattern by a Helmholtz coil. A conventional wafer probe (GSG-40-150) was put into contact with the sensor. The transmission coefficient (S_{21}) was measured by network analyzer (HP8752A) when the magnetic field was slowly changed as shown in Fig. 2. The frequency span was 300 kHz - 3 GHz, the bandwidth was 3 kHz and averaging was done 16 times in the network analyzer.

2.2 Permittivity of STO film

Fig. 3 shows a coplanar line for an evaluation of permittivity of STO film. The STO film thickness was 6 μm, which was the same as the sensor in Fig. 1. The length of the coplanar line was 2.8 mm, being free from wave length resonance up to 3 GHz. Fig. 4 shows an equivalent circuit of the coplanar line in open terminated. Fig. 5 shows a flow chart of an evaluation of permittivity

Fig. 7 Relation between capacitance of coplanar line and relative permittivity of STO film.

Fig. 8 Measured permittivity of the STO film as a function of frequency.

of STO film. Firstly coplanar line with STO film (main sample) was fabricated as shown in Fig. 3. Another coplanar line (reference sample) was deposited directly on the glass substrate without STO film as a reference. In Fig. 4, G_{STO} is conductance of STO film, C_{STO} is capacitance of STO film, G_g is conductance of glass substrate, C_g is capacitance of glass substrate, and Y_{air} is stray admittance. The capacitance (susceptance) and the conductance was obtained by reflection coefficient (S_{11}) when the coplanar line was open circuited. Then the capacitance, $C_{\text{main}} - C_{\text{ref}}$, and conductance, $G_{\text{main}} - G_{\text{ref}}$ were obtained as a contribution of the STO film. Fig. 6 shows the electric field calculation model and a cross-sectional view of the STO film and Cu film on a glass substrate. The STO film and Cu film was the same thickness as the coplanar line in Fig. 3. Input voltage of 1 V and 0 V were applied to the center conductor and outer conductors (ground plane) respectively. The DC electric field distribution and capacitance were calculated using FEM analysis (Ansoft Maxwell 2D). The permittivity of the STO film was changed from 7 to 300 as a parameter, and that of the glass substrate was 7. The calculated capacitance, $C_{\text{cal}}(\epsilon_r)$, was obtained from the integral of the electric field distribution. Then the capacitance, $C_{\text{cal}}(\epsilon_r) - C_{\text{cal}}(\epsilon_r=7)$ were obtained as a contribution of STO film. Static permittivity of STO film was optimized by equation (1) in Fig. 5. Fig. 7 shows the capacitance of the coplanar line as a function of the static permittivity of STO film. Measured capacitances (six samples), $C_{\text{main}} - C_{\text{ref}}$, were obtained around 0.09 pF,

(a) Dependence on magnetic field

(b) Dependence on frequency

Fig. 9 Phase change of sensor output.

therefore effective static relative permittivity was optimized about 31. Fig. 8 shows a complex permittivity of STO film. Real part of relative permittivity, ϵ_r' , was inversely obtained equation (2) of Fig. 5, imaginary part, ϵ_r'' , was obtained equation (3) of Fig. 5. ϵ_r' was almost constant, ϵ_r'' was quite smaller than ϵ_r' up to 3 GHz. The dissipation factor, $\tan \delta$, was obtained about 0.06 at 2 GHz.

3. Experimental Results

3.1 Phase change of the sensor

Fig. 9 shows the phase of transmission coefficient (S_{21}). Fig. 9 (a) shows the phase as a function of magnetic field, and (b) shows the phase as a function of the carrier frequency. Maximum phase change around 180 degree/Oe was obtained around 2.2 GHz and 0.8 Oe. In Fig. 9(b), the phase change increased as the frequency increased because the phase constant of the coplanar line increased as the frequency increased. Fig. 10 shows a gain of transmission coefficient (S_{21}). Fig. 10(a) shows the gain as a function of the applied field, and (b) shows the gain as a function of the carrier frequency. The gain decreased as the frequency increased because the loss of CoNbZr film and Cu film increased. The gain was obtained over -40 dB under 2.2 GHz, which is suitable for the application of magnetocardiography⁷⁾. Therefore, the sensor obtained both high phase change of 180

Fig. 10 Amplitude of sensor output.

Fig. 11 Phase change and gain of sensors.

degree/Oe and gain within -40 dB simultaneously.

Fig. 11 shows the phase change and gain when dielectric materials were STO film, SiO_2 film, or ceramic substrate. The sensor with SiO_2 film (2 μm in thickness) was fabricated with the same structure as that shown in Fig. 1, although the sensor length was 5 mm. The sensor with a ceramic substrate (50 mm x 50 mm, 0.5 mm in thickness, $\epsilon_r = 115$) was combined with large CoNbZr film (25 mm x 25 mm)⁶⁾. The sensor using STO film improved sensitivity by over 100 degree/Oe compared with the sensor using SiO_2 film because high permittivity of STO film improved sensitivity. Both sensors with STO film and the ceramic substrate had good sensitivity over 100 degree/Oe because both material has high permittivity. The gain of the sensor using STO film was slightly lower than that of the sensor using the ceramic

substrate, which was because the Cu thickness (4 μm) of the sensor using STO film was thinner than the thickness of the Cu (18 μm) using the ceramic substrate.

4. Conclusions

1. A coplanar line-type thin film sensor composed of $\text{Sr}_{33}\text{Ti}_{16}\text{O}_{51}$ film with high permittivity and amorphous CoNbZr film was developed.
2. The permittivity of the deposited $\text{Sr}_{33}\text{Ti}_{16}\text{O}_{51}$ film was estimated to be about 31.
3. The sensor has good sensitivity of over 100 degree/Oe, and gain was within -40 dB which is suitable for application to magnetocardiography (MCG).
4. The sensor with $\text{Sr}_{33}\text{Ti}_{16}\text{O}_{51}$ film with high permittivity improved the sensitivity of magnetic field detection and exhibited reasonable gain compared with the sensor with SiO_2 film with low permittivity.

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