한국정밀공학회지 제 41 권 제 12 호 pp. 991-996 December 2024 / 991
J. Korean Soc. Precis. Eng., Vol. 41, No. 12, pp. 991-996 http://doi.org/10.7736/JKSPE.024.103
ISSN 1225-9071 (Print) / 2287-8769 (Online)

Enhanced Insertion Loss and Frequency Selectivity in SAW Devices through Tailored Ag-Ti Thin Films

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KEYWORDS: Combinatorial sputtering, Surface acoustic wave, Interdigital transducer, Silver-titanium, Thin film

A compositional library of Ag-Ti thin films was fabricated using combinatorial RF magnetron sputtering. The films exhibited a gradual compositional gradient across the substrate, ranging from Ag-rich to Ti-rich compositions. SEM analysis revealed a uniform thickness of approximately 150 nm for all films. The relationship between composition and properties was investigated, demonstrating that increasing Ag content led to decreased resistivity and increased density. These results can be attributed to the high electrical conductivity and density of Ag. To optimize SAW device performance, a balance between resistivity and density must be achieved. While Ag-rich films offer higher electrical conductivity, they may experience reduced inverse piezoelectric effects due to increased density. Conversely, Ag-poor films may have improved inverse piezoelectric effects but reduced electrical conductivity.

Manuscript received: August 26, 2024 / Revised: September 24, 2024 / Accepted: September 24, 2024

NOMENCLATURE

k = Helmholtz Number
f = Resonant Frequency
c_f = Speed of Acoustic Wave in Water
c_s = Speed of Acoustic Wave in Piezoelectric Substrate
λ = Wavelength of SAWs
d = Pattern Width of IDTs

1. Introduction

Surface acoustic wave (SAW) sensors have been widely adopted in various industries due to their high frequency, low insertion loss, and exceptional performance [1-3]. A critical component of SAW sensors, the interdigital transducer (IDT), significantly influences overall sensor performance. IDTs leverage the piezoelectric effect to convert electrical energy into mechanical vibrations. Specifically, when a voltage is applied to an IDT, the inverse piezoelectric effect induces mechanical deformation, generating surface acoustic waves [4, 5]. These waves interact with substances adsorbed on the sensor surface, causing a frequency shift that can be measured to detect external environmental changes.

Traditionally, noble metals have been employed as IDT materials [6], but their high density limits the generation of high-frequency SAWs, resulting in reduced sensor sensitivity and frequency response. While aluminum [7] is suitable for generating high-frequency SAWs, its low electrical conductivity causes signal losses. These limitations have hindered the advancement of SAW sensor performance. To address these challenges, researchers have been exploring novel IDT materials with enhanced piezoelectric properties, lower density, and higher electrical conductivity. Silver-titanium (Ag-Ti) composite films exhibit promising characteristics for SAW sensor applications, including excellent electrical conductivity, low density, and superior corrosion resistance. The high electrical conductivity of Ag element ensures efficient IDT operation, while the low density of Ti element improves impedance matching with the piezoelectric substrate, enhancing surface acoustic wave generation and sensor sensitivity. Additionally, the Ti element inhibits Ag surface oxidation, maintaining stable electrical properties over time.

To systematically investigate the properties of Ag-Ti thin films with various compositions, we employed the combinatorial sputtering technique [8-10]. This technique enables the rapid fabrication of a library of thin films with different compositions, facilitating the correlation between composition and performance. By applying combinatorial sputtering to Ag-Ti composite films, we aim to systematically analyze the influence of composition on the electrode performance of SAW sensors. This approach will allow us to identify the optimal composition of Ag-Ti alloy for IDT applications, leading to improved sensitivity, selectivity, and operating frequency of SAW sensors.

2. Experimental Detail

Ag-Ti thin films with varying chemical, structural, and electrical properties were grown on 4-inch silicon (Si) substrates using combinatorial RF sputtering (ULVAC MB07-4501). These films were then systematically investigated for their application as SAW-IDT electrodes. To fabricate the Ag-Ti thin films, single metal Ag and Ti targets were employed, and the films were grown in a fixed state without substrate rotation to establish a compositional gradient. The sputtering conditions for the compositionally graded Ag-Ti thin films were as follows: RF power of 75 W (Ag) and 225 W (Ti), base pressure of 3.1×10^{-6} Pa, working pressure of 0.21 Pa, flow gas of Ar (99.99%), and room temperature substrate. The Ag-Ti thin films were subsequently cut into 5 pieces, and the structural, chemical, and electrical properties of each sample were evaluated. Two types of Ag-Ti thin films with the uniform composition were deposited on 4-inch Si substrates through rotational growth. The sputtering conditions for these films were: RF power of 75 W (Ag) and 75, 300 W (Ti), base pressure of 3.1×10^{-6} Pa, working pressure of 0.21 Pa, flow gas of Ar (99.99%), and room temperature substrate.

The SAW-IDT pattern with a straight configuration was designed to have a resonant frequency of 143 MHz. This pattern consisted of an Ag-Ti thin film thickness of 150 nm, a pattern width of 7 μm, a total IDT length of 3,000 μm, and 87 electrode pairs. The IDT electrode was patterned onto a 4-inch diameter $LiNbO_3$ (LN) substrate with a crystal orientation rotated 128 degrees from the +y axis through the +z axis about the x-axis. Before depositing the IDT electrodes, the LN wafer was cleaned using Piranha solution, and then IDT patterns were formed using photolithography with a positive photoresist (AZ GXR 601). The Ag-Ti thin films were deposited on the LN substrate using RF magnetron sputtering.

The compositional distribution and morphological properties of the Ag-Ti thin films were examined using field emission scanning microscopy (FE-SEM, Quanta 200). Electrical resistivity was determined using the Hall Effect Measurement System with van der Pauw geometry (Model 7707, Lake Shore Cryotronics) at a constant magnetic field of 4 kG. The IDT patterns were observed using a 3D laser optical microscope (Model OLS4100-SAA, OLYMPUS). The resonant frequency of the SAW device was analyzed using a Vector Network Analyzer (Model E5080B, Keysight).

3. Results and Discussion

The combinatorial RF magnetron sputtering technique was employed to construct a compositional library of Ag-Ti thin films, as shown in Fig. 1.

By systematically analyzing samples AT1 to AT5, a correlation between composition and properties was established. These samples exhibited a continuous gradient in the composition ratio of Ag and Ti, allowing for efficient screening of a wide range of compositions in a single experiment. Specifically, sample AT1, with a high Ag content, is expected to exhibit excellent electrical conductivity, while sample AT5, with a high Ti content, is anticipated to demonstrate low density. The construction of this compositional library enabled quantitative analysis of the property variations resulting from compositional changes in the Ag-Ti films, facilitating the rapid selection of optimal compositions for specific applications.

Fig. 2 shows the cross-sectional and surface images of Ag-Ti thin films deposited on a single Si substrate as a function of sample number. SEM analysis of the Ag-Ti thin films deposited on a single Si substrate revealed a uniform thickness of approximately 150 nm for all samples (AT1-AT5). This indicates the effectiveness of the combinatorial sputtering process in producing thin films with precise thickness control. Furthermore, the fabricated films are expected to exhibit a gradual compositional variation across the substrate, forming a compositional library. The excellent adhesion observed at the interface between the Ag-Ti films and the Si substrate, free from defects such as voids or cracks, demonstrates the potential of combinatorial sputtering for producing high-quality thin films.

Fig. 3 presents the compositional variation of Ag-Ti thin films fabricated through combinatorial sputtering. As the sample number

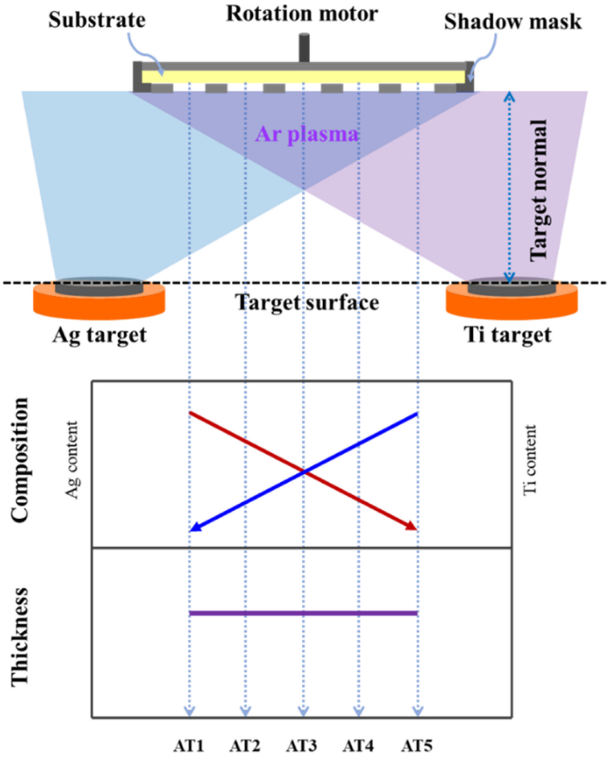


Fig. 1 Schematic diagram of a combinatorial sputtering system for the growth of Ag-Ti thin film library

increases, the Ag content decreases linearly from 84.5 to 22.4 at%, while the Ti content increases linearly from 15.5 to 77.6 at%. Notably, all samples exhibited a uniform thickness of approximately 150 nm. These findings indicate that the combinatorial sputtering process enabled the systematic control of the compositional ratio of Ag and Ti, resulting in the fabrication of thin films with a wide range of compositions.

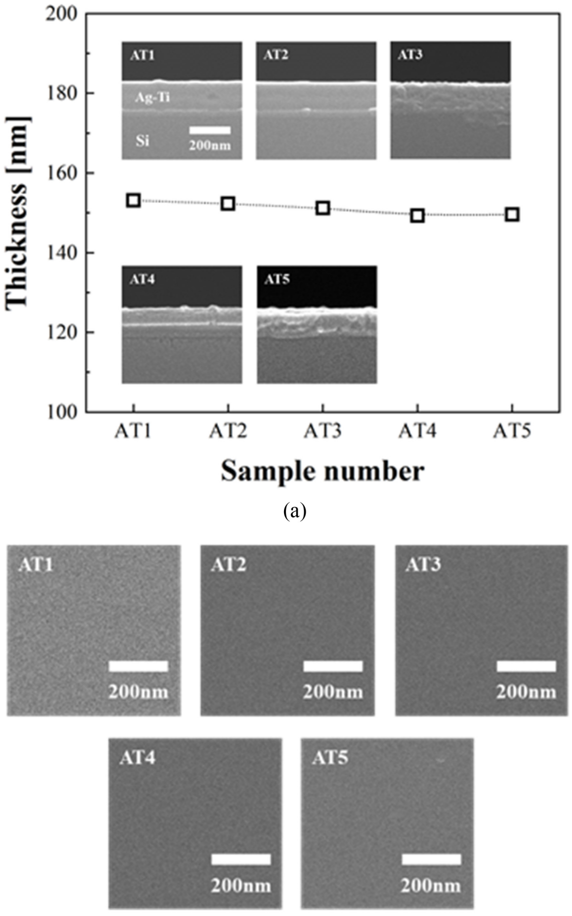
When the Ag content in Ag-Ti thin films was varied, it was observed that the resistivity decreased while the density increased as the Ag content increased. Specifically, as the Ag content increased from 22.4 to 84.5 at%, the resistivity decreased from approximately 5.6 to 1.2 × 10^{-5} Ω-cm, and the density increased from 5.8 to 9.5 g/cm³, as shown in Fig. 4.

The mixed density of the Ag-Ti thin films was calculated using the following simple equation:

$$\rho_{(Ag\text{-}Ti)} = (\rho_{Ag} \times V_{Ag} + \rho_{Ti} \times V_{Ti}) / 100,$$

where ρ represents the theoretical density and V represents the volume percentage. By converting the atomic percentages of the five Ag-Ti samples with varying Ag and Ti contents to volume percentages, the density of the Ag-Ti mixed thin films was calculated.

These results can be attributed to the high electrical conductivity and density of Ag. In other words, as the Ag content increased, charge transport within the film was facilitated, leading to a decrease in resistivity, and the increased number of Ag atoms resulted in an increase in density. IDT



(a)

(b)

Fig. 2 (a) Cross-sectional and (b) surface images of Ag-Ti thin films as a function of sample number

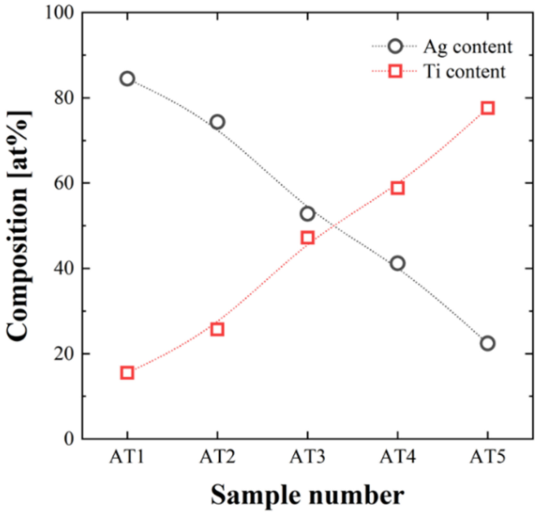


Fig. 3 Compositional variation of Ag-Ti thin films as a function of sample number

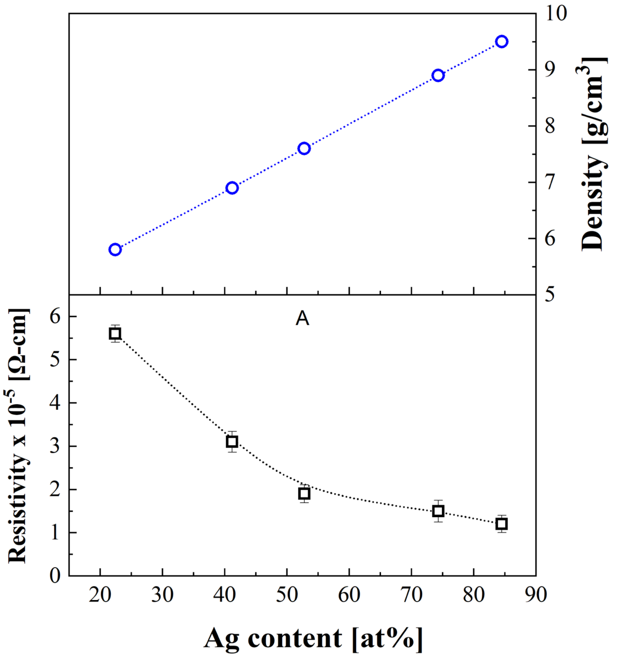
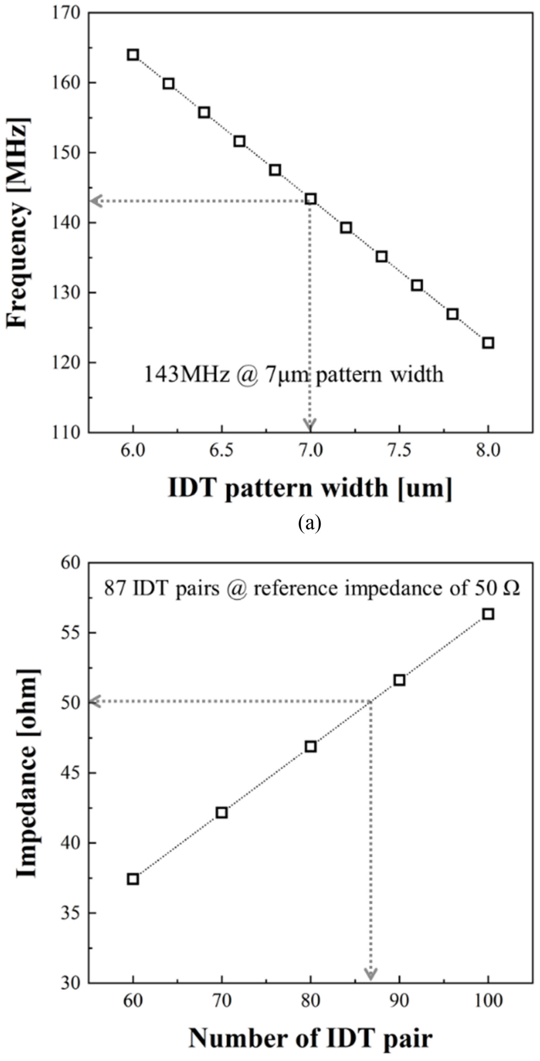


Fig. 4 Variations in resistivity and density of Ag-Ti thin films according to the Ag content



(a)

(b)

Fig. 5 Relationship between (a) resonant frequency and IDT pattern width and (b) the number of IDT electrode pairs and the total IDT length analyzed by Mathematica

electrodes, a key component of SAW devices, require high electrical conductivity and low density to achieve efficient inverse-piezoelectric effects. Therefore, based on our findings, Ag-Ti thin films with high Ag content can achieve high electrical conductivity but may experience a decrease in inverse piezoelectric effects due to increased density.

Conversely, films with low Ag content may exhibit improved inverse piezoelectric effects but have reduced electrical conductivity. To optimize the performance of SAW devices, a trade-off between resistivity and density must be achieved. In other words, it is essential to find the optimal Ag content where the resistivity is not too high and the density is at an appropriate level.

To effectively control microparticles in microfluidic devices using the SAWs, it's essential to select a suitable SAW-IDT electrode material. The specific resonant frequency of the SAW device is crucial for controlling particles of a given size. For polystyrene microparticles with a diameter of 5 μm, the Mie scattering condition must be satisfied to ensure precise control. This condition requires a specific Helmholtz number (*k*). Using the following equation [11];

$$k = \pi f \, d \; / \; c_f$$

where f is the resonant frequency and c_f is the speed of acoustic wave in water, we calculated the resonant frequency to be 143 MHz. To achieve this resonant frequency, the acoustic frequency must be calculated using the following equation [12];

$$f = c_s \; / \; \lambda$$

where c_s is the speed of acoustic wave in the piezoelectric substrate and λ is the wavelength of SAWs. The wavelength of SAWs is determined by the IDT pattern width (d) according to the following equation [12];

$$\lambda = 4d$$

As shown in Fig. 5, the relationship between IDT pattern width, number of electrodes, film thickness, and total electrode length was analyzed using Mathematica, revealing that the IDT pattern width significantly influences the resonant frequency. To obtain the desired resonant frequency of 143 MHz for controlling

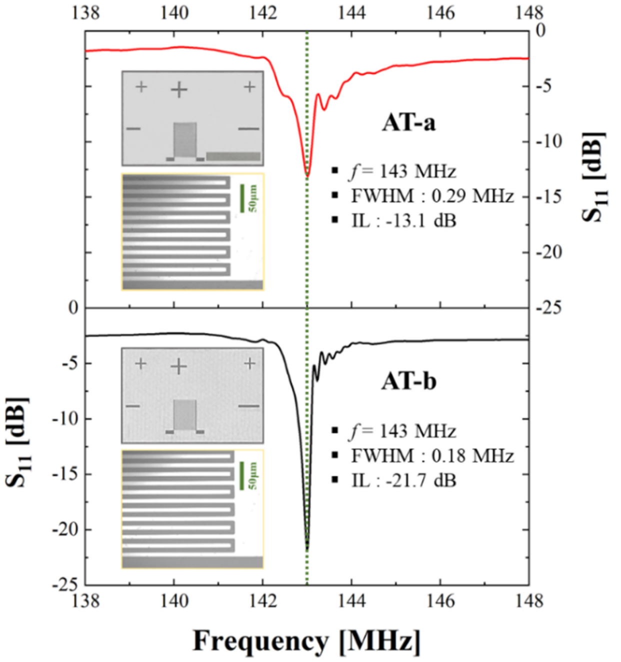


Fig. 6 Resonant frequency of SAW devices composed of Ag-Ti electrodes with different Ag content

5 μm polystyrene particles, an IDT pattern width of 7 μm is necessary. Additionally, 87 IDT electrode pairs and a total IDT length of 3,000 μm were selected to ensure a reference impedance of 50 Ω.

To compare the acoustic properties of SAW devices fabricated with Ag-Ti thin films, S11 parameter measurements were conducted on AT-a and AT-b SAW devices, with IDT electrode Ag compositions of 81.3 and 19.8 at%, respectively. As shown in Fig. 6, both devices exhibited a resonant frequency near 143 MHz. However, the AT-b device demonstrated a narrower bandwidth of 0.18 MHz and a lower insertion loss of -21.7 dB compared to the AT-a device.

This can be attributed to the decreased average density of the Ag-Ti thin film in the AT-b device due to its lower Ag content, leading to an increased mechanical quality factor of the SAW device. While the electrical and structural characteristics of the IDT electrode undoubtedly influence the overall performance of the SAW device, our findings suggest that the density of the IDT electrode plays a dominant role in determining its acoustic performance. In other words, the electrical energy applied from the IDT electrode is converted into mechanical energy, which expands or contracts the crystals of the piezoelectric material via the inverse piezoelectric effect. The high density of the IDT electrode formed in the piezoelectric material could locally restrict the generation of acoustic waves, thereby weakening the insertion loss and selectivity of the resonant frequency. As shown in Fig. 6, the AT-b device with the lowest Ag content of 19.8 at% exhibited a significant 65% improvement in insertion loss compared to the AT-a device with a higher Ag content of 81.3 at%. This suggests that the reduction in Ag content leads to a decrease in film density, consequently altering the sound velocity and resulting in lower insertion loss. Therefore, the mechanical properties, specifically density, of Ag content appear to have a more dominant influence on the insertion loss of SAW devices.

4. Conclusion

The combinatorial RF magnetron sputtering technique effectively produced a compositional library of Ag-Ti thin films, spanning a wide range of Ag and Ti compositions. The fabricated films demonstrated uniform thickness and excellent adhesion to the Si substrate, confirming the efficacy of the combinatorial sputtering process. Analysis of the compositional library revealed a strong correlation between Ag content and film properties. As Ag content increased, resistivity decreased while density increased, primarily due to the high electrical conductivity and density of Ag. This trend suggests that Ag-Ti thin films with high Ag content are suitable for applications requiring high electrical conductivity, but may compromise inverse-piezoelectric effects due to increased density. Conversely, films with low Ag content exhibit improved inverse piezoelectric effects but have reduced electrical conductivity. To optimize SAW device performance, balancing resistivity and density is crucial. While high Ag content can enhance electrical conductivity, it may hinder inverse piezoelectric effects. Therefore, identifying the optimal Ag content that strikes a balance between these two properties is essential for developing high-performance SAW devices.

ACKNOWLEDGEMENT

This study was conducted with the support of the Korea Institute of Industrial Technology and the Korea Industrial Complex Corporation as a “Competitiveness reinforcement project for industrial clusters(1415189052)”.

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