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Ni-Cr-Mn-Y-Nb resistive thin film prepared by co-sputtering

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HIGHLIGHTS

- High resistivity with low-TCR of thin film resistors can be fabricated.
- *TCR* of thin film can be adjusted to close to zero by annealing process and Nb content.
- Ni-Cr-Mn-Y films with 14% Nb annealed at 300 °C exhibited excellent electrical properties.

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ABSTRACT

A Ni-Cr-Mn-Y-Nb resistive thin film was prepared in this study using DC and RF magnetron co-sputtering from $Ni_{0.45}$-$Cr_{0.27}$-$Mn_{0.13}$-$Y_{0.16}$ cast alloy and niobium targets. The electrical properties and microstructures of Ni-Cr-Mn-Y films with Nb addition under various annealing temperatures were investigated. The phase evolution, microstructure and composition of Ni-Cr-Mn-Y and Ni-Cr-Mn-Y-Nb films were characterized using X-ray diffraction (XRD), field-emission scanning electron microscopy (FESEM), field-emission transmission electron microscopy (HRTEM). All Ni-Cr-Mn-Y-Nb films annealed at 300 °C exhibited an amorphous structure. The $Ni_{17}Y_{12}$ crystalline phase was observed in Ni-Cr-Mn-Y-Nb films with or without lower Nb content when annealed at 400 °C. When the annealing temperature was set to 300 °C, the Ni-Cr-Mn-Y films exhibited a resistivity ~480 μΩ-cm with the temperature coefficient of resistance (*TCR*) at +30 ppm/°C. However, Ni-Cr-Mn-Y films with 14 at.% Nb exhibited the smallest temperature coefficient of resistance (+5 ppm/°C) with the resistivity ~585 μΩ-cm after annealing at 300 C in air.

1. Introduction

The rapid development and improvement of information and telecommunication technologies as well as the expansion of digital industries are based to a substantial degree on high precision, reliable, integrated, low noise and low power consuming electrical components [1]. The resistor is one of the fundamental components used primarily in electronic circuits. The demand for thin film resistors with low temperature coefficients of resistance (*TCR*) and high precision has dramatically increased in recent years. [2-5]

An important technical parameter of thin film resistors is the temperature coefficient of resistance (*TCR*). A high *TCR* will result in the resistance value drifting, influencing the resistor accuracy as the temperature changes [6]. The main factors influencing *TCR* include the film composition, sputtering process and annealing temperature. The film composition plays a decisive role among these three factors. Therefore, employing an appropriate method for depositing a suitable film composition is essential to obtaining high-resistance resistors with a low *TCR*.

Extensive rapid development in high entropy alloy (HEA) film were obtained recent years by Yeh [7]. High entropy alloys are multicomponent systems composed of elements displaying a nearly equiatomic configuration with contents ranging between 5 and 35 at.% [8]. It was generally found that high entropy alloys form simple solid solution structures (rather than many complex phases) at elevated temperatures because of their large mixing entropies. However, it is possible to enhance the resistivity of alloy films using the high entropy alloy method. According to Matthiessen's rule: [9]

$$\rho_{total} = \rho_{defects} + \rho_{impurities} + \rho_{thermal}$$

That is the total resistivity is composed of independent

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contributions from the defects, impurities and thermal vibrations in the metal.

Ni-Cr thin films are applied in integrated circuits, where good power dissipation, low noise and a near-zero temperature coefficient of resistance are important. Several papers have reported on the deposition of Ni-Cr resistive films using thermal evaporation [10-13] and radio frequency (RF) sputtering, primarily for use as hybrid resistors. [14,15]

The temperature coefficient of resistance (TCR) of thin film resistors is a measure of the change in resistance with a change in temperature, generally expressed in parts per million per degree centigrade (ppm/°C). It is a figure of merit for the resistor's stability through temperature changes. An increase in resistance with an increase in temperature is defined as a positive TCR, while a decrease in resistance with an increase in temperature is defined as a negative TCR. The TCR and resistivity of thin films have been studied for various NiCr-based alloy compositions prepared by adding Si, Al, Mn, Ta, etc. to binary Ni-Cr alloys [16-19]. Annealing is a key process that improves long-term thin film stability. It also improves the consistency of the TCR values. Annealing treatment effects on NiCr-based thin film resistors has also been reported [20-22].

Niobium, with a high melting point at 2477 °C, is beneficial for resistive thin film thermal stability. Rare earth (RE) doping has been widely used as an effective approach for regulating the electrical properties of oxides [23-25]. Yttrium addition was attempted to improve the electrical properties of resistive films. Manganese, on the other hand, is a transition metal ($T_m = 1245$ °C). Manganese is a moderately active metal. It combines slowly with the oxygen in air to form manganese dioxide, which may be helpful to improve *TCR*. In obtaining resistive films with high resistivity and low *TCR*, the high entropy alloy concept was introduced to investigate the Ni-Cr-Mn-Y-Nb composition as thin film resistors. The effects of the Nb content and annealing temperature on the phases, microstructural and electrical properties of Ni-Cr-Mn-Y-Nb thin films are investigated in this study.

2. Experimental procedure

2.1. Ni-Cr-Mn-Y thin film

Nickel (Ni), Chromium (Cr), Manganese (Mn), and Yttrium (Y) powders, as the main raw materials, were chosen to smelt the target for high-resistance thin film resistors. Alloy films were deposited onto polished alumina (Al_2O_3) substrates. These alumina substrate were scribed for the TCR measurement into 1.6 × 0.8 mm cell sizes using a laser. Glass and Si wafers were used as substrates for the sheet-resistance measurements and thin film thickness, respectively. These substrates were cleaned using a D.I. water-cleaning procedure and dried in nitrogen before loading into the sputtering chamber.

Ni-Cr-Mn-Y thin films that were 80 nm in thickness were deposited onto the substrates using a DC magnetron sputtering system. A $Ni_{0.45}$-$Cr_{0.27}$-$Mn_{0.13}$-$Y_{0.16}$ alloy with a diameter 76.2 mm was used as targets. The DC power was fixed at 50 W. The sputtering chamber was evacuated to a background pressure of 5×10^{-7} torr using a cryo-pump. Sputtering was performed using argon gas with a purity of 99.999% at flow of 60 sccm using mass flow controllers at a working pressure of 3×10^{-3} torr for gas introduction into the chamber.

2.2. Ni-Cr-Mn-Y-Nb thin film

The niobium target was made from Nb powders, which is helpful to improved TCR and stabled film structure. Ni-Cr-Mn-Y-Nb thin films 80 nm in thickness were deposited onto the substrates using a DC and RF magnetron co-sputtering system. A $Ni_{0.45}$-$Cr_{0.27}$-$Mn_{0.13}$-$Y_{0.16}$ alloy and niobium with a diameter 76.2 mm were used as targets. The Ni-Cr-Mn-Y alloy target was set at the DC position. The niobium target with a diameter 76.2 mm was set at the RF position. To obtain different niobium contents in the Ni-Cr-Mn-Y film, the DC power was fixed at 50 W and the RF power was changed from 20 W to 120 W. The sputtering chamber was evacuated to a background pressure of 5×10^{-7} torr using a cryo-pump. Sputtering argon gas with a purity of 99.999% at flow of 60 sccm was performed using mass flow controllers with a working pressure of 3×10^{-3} torr.

2.3. Analysis

Thin films deposited onto glass plates at room temperature were subjected to transmission electron microscopy (TEM) and X-ray diffraction (XRD) studies, Thin films deposited onto Al_2O_3 substrates (size: 400 mm^2) were used to measure the electrical properties. The substrate temperature was 25 °C. The as-deposited films were annealed at 250–400 °C for 2 h, at a heating rate of 5 °C/min in air.

The sheet resistance R_s of the films was measured using the four-point probe technique. The thickness t of the films was measured using FE-SEM (cross-section). The resistivity measured using the four-probe method was consistent with the resistivity obtained by the R_s and t samples. The *TCR* values of the thin films were measured using thin long strips cleaved from the substrate. Electrical contacts at the two ends of the resistive strips were obtained by selectively coating the ends with sputtered silver. The DC resistance of the strips was measured using a digital multimeter (HP 34401A) at different temperatures (25 °C and 125 °C). The *TCR* of the thin films was measured using the following equation

$$\mathrm{TCR} = [(\Delta R/\Delta T) \times 1/R] \times 10^6 \ \mathrm{ppm/K} \quad (1)$$

The deposited films composition of was determined using Auger Electron Spectroscopy (AES). The AES depth profiles were obtained in a PHI 550ESCA/SAM Auger microprobe (Physical Electronics, USA). The film crystallinity was analyzed using X-ray diffraction (XRD, Bruker D8A Germany), using Cu K_α radiation for 2θ values from 10° to 80°, with a scan speed of 3° min^{-1} and a grazing angle of

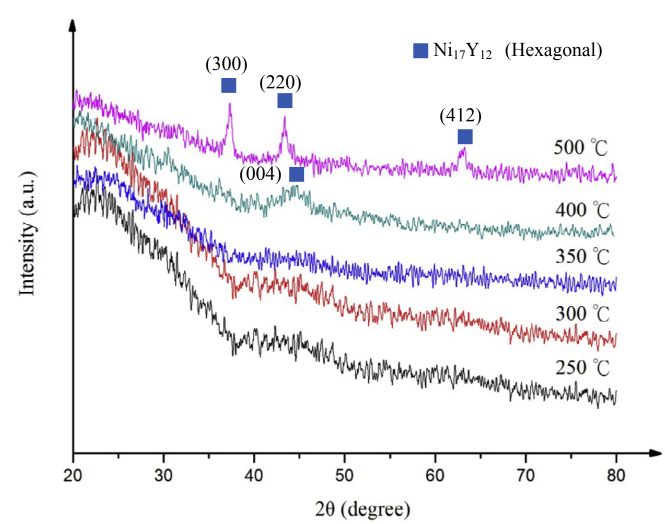

Fig. 1. X-ray diffraction patterns of Ni-Cr-Mn-Y thin films annealed at different temperatures.

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