

# Developments of Cr-Si and Ni-Cr Single-Layer Thin-Film Resistors and a Bi-Layer Thin-Film Resistor with Adjustable Temperature Coefficient of Resistor

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## Abstract

At first, Cr-Si (28 wt% Cr, 72 wt% Si) and Ni-Cr (80 wt% Ni, 20 wt% Cr) thin-film materials were deposited by using sputtering method at the same parameters, and their physical and electrical properties were investigated. The resistances of Cr-Si and Ni-Cr thin-film resistors decreased with the increase of deposition time (thickness) and their resistivity had no apparent variations as the deposition time increased. The temperature coefficient of resistance (TCR) of single-layer Cr-Si thin-film resistors was negative and the TCR value of single-layer Ni-Cr thin-film resistors was positive. For that, we used Cr-Si thin films as upper (or lower) layer and Ni-Cr thin films as lower (upper) layer to investigate a bi-layer thin-film structure. The deposition time of Ni-Cr thin films was fixed at 10 min and the deposition time of Cr-Si thin films was changed from 10 min to 60 min. We had found that as Cr-Si thin films were used as upper or lower layers they had similar deposition rates. We had also found that the thickness and stack method of Cr-Si thin films had large effects on the resistance and TCR values of the bi-layer thin-film resistors.

## Keywords

Cr-Si, Ni-Cr, Sputtering Method, Sheet Resistance, Bi-Layer Structure

## 1. Introduction

A resistor is a passive two-terminal electrical component that implements electrical re-

sistance, and it can act as a circuit element to reduce current flow and to lower voltage levels within circuits. Thick-film resistors became popular during the 1970s, and most surface mount device (SMD) resistors today have used this type of resistors. The thickness of thick-film resistive elements is 1000 times thicker than that of thin-film resistive elements, but the principal difference is how the thin-film resistors can be applied as the cylinder (axial) resistors or the surface resistors. Nevertheless, the noise levels of thin-film resistors are on the level of 10 - 100 times less than those of thick-film resistors. In integrated circuits (ICs) fabrication technologies, thin-film resistors can be fabricated by depositing thin films on the wafers' surfaces or using diffusion methods in the base and emitter regions of bipolar transistor and in source and drain regions of CMOS.

Thin films can be made by sputtering-based method because the deposition time during the sputtering process can be well controlled, then the thickness of deposited thin films can be accurately controlled. Sputtering-based method had been used for producing cermet thin-film resistors since the 1960s [1]. In the past, many different sputtering methods were investigated to deposit thin-film resistive materials onto different insulating substrates. Those materials usually consists of one kind of ceramic (cermet) conductor, for example tantalum nitride (TaN) [2] and ruthenium oxide (RuO<sub>2</sub>) [3]. In the past, many different sputtering methods had been investigated to deposit thin-film resistors, such as the radio-frequency (RF) magnetron sputtering [4] [5], co-sputtering techniques [6], DC magnetron sputtering process [7], DC reactive magnetron sputtering [8], and ion beam sputter deposition [9], respectively.

Thin-film heaters have been developed for many applications including chemical gas sensors. Cr-Si-based materials are a good thin-film heater candidate because they have good temperature uniformity, a high thermal efficiency, and a large thermal capacity [10] [11]. Cr-Si-based thin films are also the interesting materials to be deposited as the thin-film resistors because of certain advantages as they are used as the thin-film resistors. For example, they can be applied in low-power monolithic and hybrid integrated circuits [12]. Also, Cr-Si-based thin-film resistors have the merits of high sheet resistance, low temperature coefficient of resistance (TCR), high thermal stability, good long-term reliability, and good chemical stability [13], respectively.

A major application of high temperature superconductors is the developments of tapes and cables for low loss conduction of high density electric currents. A series of biaxially textured Ni<sub>1-x</sub>Cr<sub>x</sub> materials have been majorly studied for use as substrate materials in coated conductor applications with high temperature superconductors [14]. Excellent wear and corrosion resistance makes Ni-Cr-based thin films be an attractive material for fusible links in programmable read only memories (ROM). Recently, thin-film resistors have been used to replace the semiconductor resistors in GaAs monolithic microwave integrated circuits (MMICs). Ni-Cr-based thin films have the properties of low noise, good power dissipation, and near zero TCR value, which are important requirements for applications in MMICs [15].

In this study, Cr-Si (28 wt% Cr, 72 wt% Si) and Ni-Cr (80 wt% Ni, 20 wt% Cr) com-

positions were used as the targets and RF magnetron sputtering was used as the method to deposit the Cr-Si and Ni-Cr thin films at room temperature on  $\text{Al}_2\text{O}_3$  and Si substrates under different deposition time. After deposition, the crystallizations of the Cr-Si and Ni-Cr thin films were measured using the X-ray diffraction patterns, we had found that the Cr-Si and Ni-Cr thin films revealed the amorphous phase independent of deposition time. The sheet resistances of the Cr-Si and Ni-Cr thin-film resistors were measured, and the TCR values of the Cr-Si and Ni-Cr thin-film resistors were also measured. We had found that the TCR values of Cr-Si thin thin-film resistors were negative and the TCR values of Ni-Cr thin-film resistors were positive. For that, a bi-layer thin-film resistor, by stacking Cr-Si and Ni-Cr thin films, were investigated. We would show that the bi-layer thin-film structure could be explored to fabricate thin-film resistors with the TCR values close 0 ppm/ $^\circ\text{C}$ .

## 2. Materials and Methods

Commercial-grade composition materials Cr-Si (28 wt% Cr, 72 wt% Si) and Ni-Cr (80 wt% Ni, 20 wt% Cr) were used as the targets and the sputtering method was used to deposit Cr-Si and Ni-Cr thin films on  $\text{Al}_2\text{O}_3$  and Si substrates. The structure of deposited Cr-Si and Ni-Cr thin films used for the measurements of physical and electrical properties was investigated in [16]. The green glass paste on  $\text{Al}_2\text{O}_3$  ceramic was used to protect the substrate, and it could be removed after the deposition processes of Cr-Si and Ni-Cr thin-film resistors and following ultrasonic clean in ethyl alcohol. The length between two electrodes (or called the length of thin-film resistors) was 4.0 mm, the widths of thin-film resistors and electrodes were 2.8 mm, and the length and thickness of Ag electrodes were 1.2 mm and about 15  $\mu\text{m}$ , respectively. About the reason for using Ag as the electrode of the thin film resistor is that the Ag is the metal having the lowest resistivity and it is cheaper than Au and Pt. The deposition parameters of Cr-Si and Ni-Cr thin films were power of 150 W, pressure of 5 m Torr, and temperature of  $25^\circ\text{C}$ , and the deposition time was 10 min, 30 min, 40 min, 60 min, 90 min, and 120 min, respectively.

The Cr-Si and Ni-Cr thin films were deposited on Si-based substrates for thickness's measurements and deposited on  $\text{Al}_2\text{O}_3$ -based substrates for electrical measurements. The crystalline structure of deposited Ni-Cr and Cr-Si thin-films was determined by means of X-ray diffraction (XRD) (Cu-K $\alpha$ , Bruker D8). The surface and cross-sectional observations were carried out by using the field-effect scanning electronic microscope (FESEM). The thickness measurements of single-layer Cr-Si and Ni-Cr thin films and bi-layer thin films were obtained by using an  $\alpha$ -step equipment and confirmed with the FESEM. Also, the surface and cross-sectional observations of single-layer Ni-Cr and Cr-Si thin films and the cross-sectional observations of bi-layer thin films were measured with FESEM.

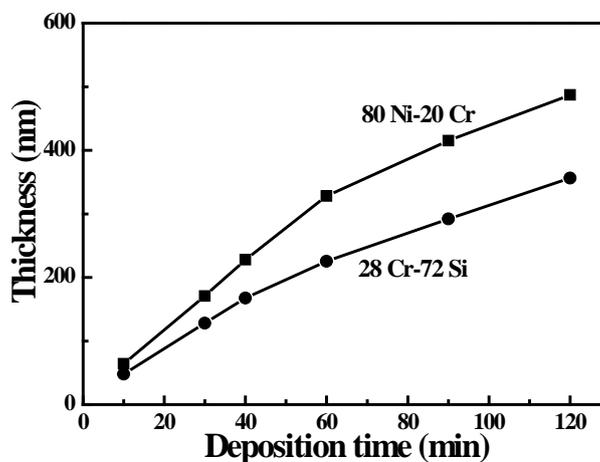
Resistance values for most materials at any temperature other than the reference temperature (usually specified at  $0^\circ\text{C}$  or at  $20^\circ\text{C}$ ) can be determined through the following formula:

$$R = \rho(A/l) = R_{\text{ref}} [1 + \alpha(T - T_{\text{ref}})] = \rho_{\text{ref}}(A/l) [1 + \alpha(T - T_{\text{ref}})] \quad (1)$$

where  $R$  is the material resistance at temperature  $T$ ,  $T_{\text{ref}}$  and  $\rho_{\text{ref}}$  are the material resistance and resistivity at reference temperature  $T_{\text{ref}}$ ,  $T_{\text{ref}}$  is the reference temperature,  $A$ ,  $l$ , and  $\alpha$  are the area, length, and temperature coefficient of resistance (TCR) value specified for a material, and  $T$  is the material temperature in degrees Celcius, respectively. In this study, the measured temperatures were 25°C, 50°C, 75°C, 100°C, and 125°C, respectively, the resistivity measured at two different temperatures were used to find the TCR values of Cr-Si and Ni-Cr thin-film resistors. The resistances, resistivity, and TCR values of Cr-Si, Ni-Cr thin-film, and bi-layer thin-film resistors were obtained by using the average value of five measured results.

### 3. Results and Discussion

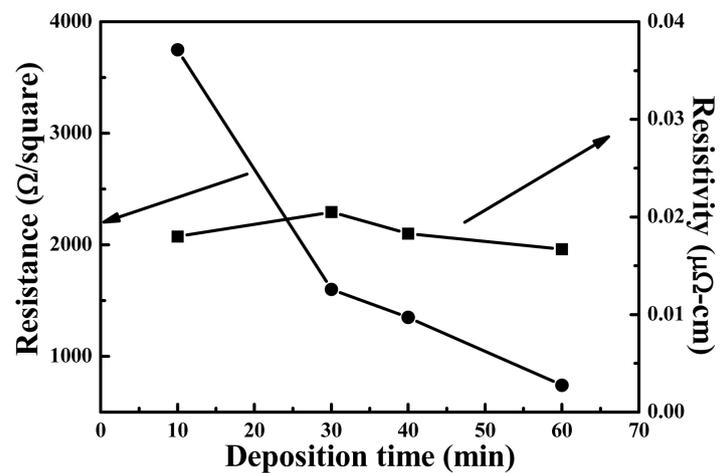
We had found that the aggregated particle sizes of the Cr-Si and Ni-Cr thin films increased with the increase of deposition time (not shown here) even both of them revealed the amorphous phase. The effect of deposition time on the thicknesses of Cr-Si and Ni-Cr thin films was investigated, and the results are shown in **Figure 1**. As 25°C was used as the deposition temperature, the thicknesses of the 10 min-, 30 min-, 40 min-, 60 min-, 90 min-, and 120 min-deposited Cr-Si thin films were about 48.0 nm, 128.1 nm, 167.4 nm, 225.4 nm, 292.0 nm, and 356.2 nm, and the thicknesses of the 10 min-, 30 min-, 40 min-, 60 min-, 90 min-, and 120 min-deposited Ni-Cr thin films were about 64.3 nm, 170.7 nm, 228.0 nm, 327.9 nm, 415.2 nm, and 487.1 nm, respectively. As the deposition time increases, the increases in the thicknesses of Cr-Si and Ni-Cr thin films are expectable. The results in **Figure 1** suggest that the deposition rate of Ni-Cr thin films is larger than that of Cr-Si thin films. Those results in **Figure 1** also suggest that as the deposition time is equal to and less than 60 min, the thicknesses of Cr-Si and Ni-Cr thin films linearly increases with the increase of deposition time. For that, the electrical properties of thin films with deposition time less than and equal to 60 min can be used to investigate the bi-layer thin-film resistors.



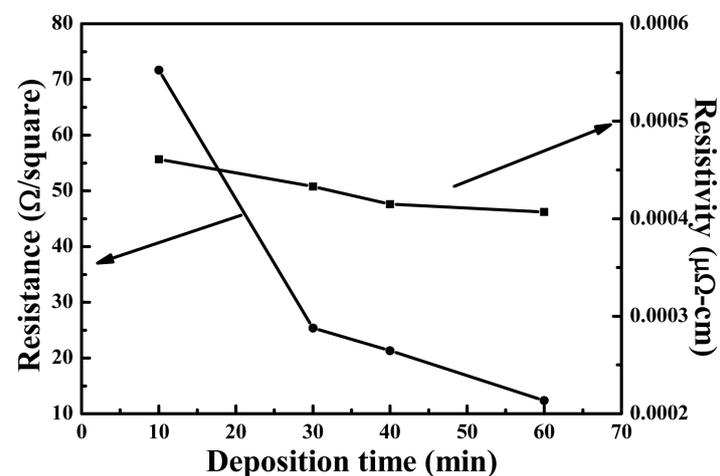
**Figure 1.** Variations of thicknesses of Cr-Si and Ni-Cr thin films as a function of deposition time.

The resistances of Cr-Si and Ni-Cr thin-film resistors were recorded by the four-point measurement. **Figure 2** shows the effect of deposition time on the variations of resistances and on the variations of resistivity obtained from the results measured at 25°C. **Figure 2(a)** and **Figure 2(b)** show that the resistances of Cr-Si and Ni-Cr thin-film resistors non-linearly decreased with the increase of deposition time. If we suppose the thicknesses of Cr-Si and Ni-Cr thin-film resistors are independent of measured temperature, then the resistivity can be derived from the measured resistances shown in **Figure 2** and the thin films' thicknesses shown in **Figure 1**. As the thin films' thicknesses increased, the variation in the resistivity of Cr-Si thin-film resistors (**Figure 2(a)**) had no apparent trend and the resistivity of Ni-Cr thin-film resistors slightly decreased (**Figure 2(b)**).

The TCR values of Cr-Si and Ni-Cr thin-film resistors were measured by using the results obtained in **Figure 2** and the results are shown in **Figure 3** as a function of thin

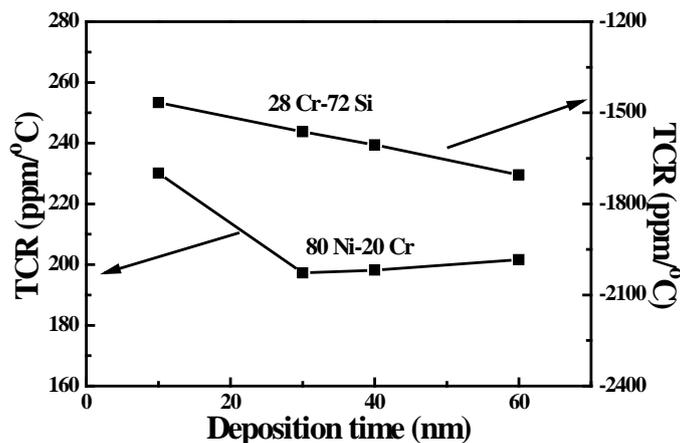


(a)



(b)

**Figure 2.** Variations of 25°C-measured resistance and resistivity of (a) Cr-Si and (b) Ni-Cr thin-film resistors as a function of deposition time, respectively.



**Figure 3.** Variations of TCR values of Cr-Si and Ni-Cr thin-film resistors as a function of deposition time.

films' thicknesses. The TCR value of element silicon (Si) in the type of single crystalline is negative with the number of about  $-40,000$  ppm/°C (depending strongly on the presence of impurities in the material). The TCR values of most pure metals are positive, it means that resistance increases with the increase of measuring temperature. The TCR value of Cr metal is  $0.13$  ppm/°C, for that Cr metal can be added in the Si to change the TCR values. As **Figure 3** shows, the TCR values of Cr-Si thin-film resistors were negative, the value was  $-1467$  ppm/°C,  $-1563$  ppm/°C,  $-1605$  ppm/°C, and  $-1704$  ppm/°C as the deposition time was 10 min, 30 min, 40 min, and 60 min, respectively. Those results prove that resistances of Cr-Si thin-film resistors decrease with the increase of measuring temperature. Because the TCR values of Cr-Si thin-film resistors have the smaller negative values than that of Si has, we believe that those results are caused by the addition of Cr metal in Si because the TCR value of Cr metal is positive. The TCR value of Ni metal is  $170$  ppm/°C, which also means that resistance of Ni metal will increase with the increase of measuring temperature. Nevertheless, the TCR values of as-deposited Ni-Cr thin-film resistors had a positive number and they were  $230$  ppm/°C,  $197$  ppm/°C,  $198$  ppm/°C, and  $202$  ppm/°C as the deposition time was 10 min, 30 min, 40 min, and 60 min, respectively. Those results show that the TCR values of Ni-Cr thin-film resistors have larger positive values than those of Ni and Cr metals do. Those results suggest again that we can use the Cr-Si and Ni-Cr thin-film resistors to investigate the bi-layer thin-film resistors.

The mixing rule for the estimation of conductivity in classical form is [17]:

$$\sigma^\alpha = (1-f) \times \sigma_M^\alpha + f \times \sigma_N^\alpha \quad (2)$$

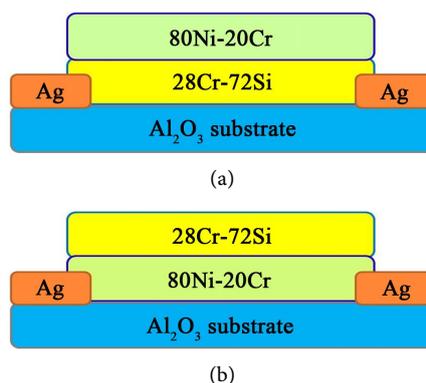
where  $f$  is the volume fraction of  $N$ ;  $\sigma_M^\alpha$  and  $\sigma_N^\alpha$  are conductivity of the phases  $M$  and  $N$ , and  $-1 < a < 1$ , and the  $\sigma = 1/\rho$ . If resistivity  $\rho$  in Equation (1) is used to substitute in Equation (2), then mixing rule for the estimation of resistivity and TCR value will be:

$$\sigma^\alpha = \left( 1/\rho \left[ 1 + \alpha(T - T_{ref}) \right] \right)^\alpha$$

$$\begin{aligned}\sigma^\alpha &= \left(1/\rho \left[1 + \alpha(T - T_{ref})\right]\right)^\alpha \\ &= (1-f) \left/ \left\{ \rho_M^\alpha \left[1 + \alpha_M^\alpha(T - T_{ref})\right]\right\} \right. + f \left/ \left\{ \rho_N^\alpha \left[1 + \alpha_N^\alpha(T - T_{ref})\right]\right\} \right.\end{aligned}\quad (3)$$

Equation (3) suggests that the resistivity ( $\rho$ ) and the TCR value ( $\alpha$ ) in each material are the two important factors to influence the TCR value of a composite with two differently dispersed materials. As we know, TCR values of Cr and Ni metals and Si are 0.13 ppm/°C, 170 ppm/°C, and -40,000 ppm/°C, respectively. Because the composition of Ni-Cr is 80 wt% Ni and 20 wt% Cr, as Equation (3) is used measured the TCR value of Ni-Cr thin-film resistors, they will have a TCR value between 0.13 ppm/°C and 170 ppm/°C. Nevertheless, the TCR value of Ni-Cr thin-film resistors is in the range of 197 ppm/°C - 230 ppm/°C as their thickness increases from 48.0 nm to 225.4 nm. Those results suggest that except the resistivity ( $\rho$ ) and the TCR value ( $\alpha$ ) in each material, there are other unknown parameters will influence the TCR value ( $\alpha$ ) of a composite with two differently dispersed materials. However, as the thickness increased from 48.0 nm to 225.4 nm, the TCR value of Ni-Cr (80 wt% Ni, 20 wt% Cr) thin-film resistors was changed from -1467 ppm/°C to -1864 ppm/°C, which was shifted to larger negative value. Those results suggest that the thickness is another important parameter, which will influence the TCR value of thin-film resistors.

Because the TCR values of Cr-Si thin-film resistors are negative and the TCR values of Ni-Cr thin-film resistors are positive, a novel bi-layer thin-film resistor is also investigated in this study to find the thin-film resistors with TCR value closing the 0 ppm/°C. In order to simply the fabrication process, the deposition time of Ni-Cr thin films was fixed at 10 min, and the deposition time of Cr-Si thin films was 10, 30, 40, and 60 min, respectively. The bi-layer thin-film resistors had two different stacking methods, the first was used Ni-Cr thin films as the upper layer and Cr-Si thin films as lower layer, as **Figure 4(a)** shows; The second was used Ni-Cr thin films as the lower layer and Cr-Si thin films as upper layer, as **Figure 4(b)** shows. As **Figure 4** shows, the two thin-film resistors in the bi-layer thin-film structure are in parallel, the resistance can be expressed as:

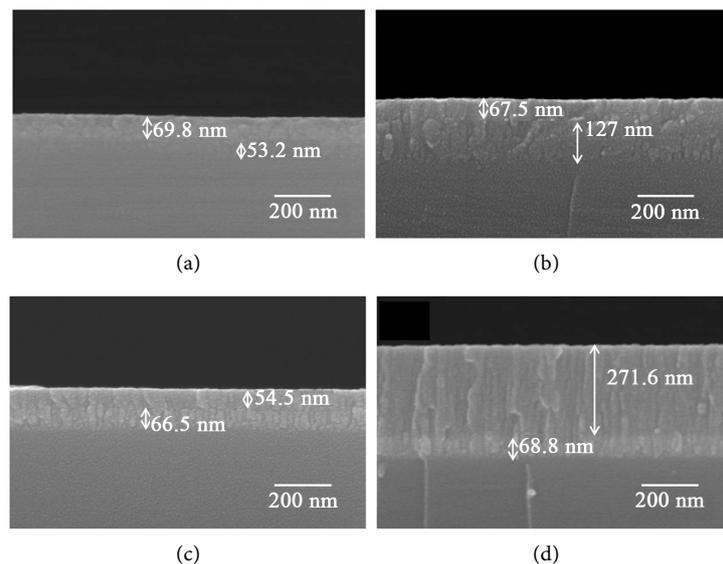


**Figure 4.** Structures of two different bi-layer thin-film resistors. (a) Ni-Cr thin films as the upper layer and Cr-Si thin films as lower layer and (b) Ni-Cr thin films as the lower layer and Cr-Si thin films as upper layer.

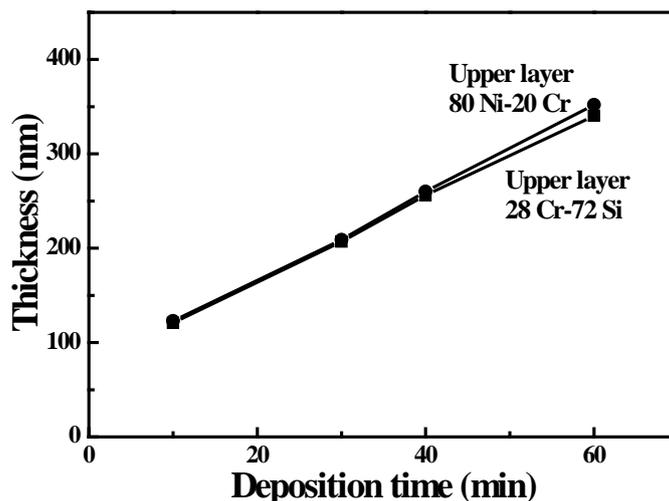
$$R_{eq} = (R_{Ni-Cr} \times R_{CrSi}) / (R_{Ni-Cr} + R_{CrSi}) \quad (4)$$

where  $R_{eq}$  is equivalent resistance and  $R_{Ni-Cr}$  and  $R_{Cr-Si}$  are the resistances of Ni-Cr and Cr-Si thin-film resistors, respectively. From **Figure 3** we know that  $R_{Ni-Cr}$  (TCR value is positive) increases and  $R_{Cr-Si}$  (TCR value is negative) decreases as the measured temperature increases. From Equation (4) we know that the variation of  $R_{eq}$  will decrease as Ni-Cr and Cr-Si thin-film resistors are in parallel, it means the TCR value will be decreased in the bi-layer structure.

Because the deposition rate of Cr-Si thin films is smaller than that of Ni-Cr thin films, as **Figure 1** shows. In order to obtain the predictable and controllable thickness, the deposition time of Ni-Cr thin films was set at 10 min and the deposition time of Cr-Si thin films was changed from 10 min to 60 min. The cross-section observations of the bi-layer thin-film resistors with different structures and with different deposition time of Cr-Si thin films were shown in **Figure 5**, the bi-layer structure was apparently observed. The cross-section images show that even the two layers are really revealed because of their different growing morphologies, the splitting between Cr-Si and Ni-Cr thin films is not apparently observed. **Figure 6** shows that the variations in the thickness of bi-layer thin-film resistors. No matter the 10 min-deposited Ni-Cr thin films were used as upper layer or lower layer, their thicknesses were in the range of 66.5 - 69.8 nm, which is similar to the value obtained from the single layer shown in **Figure 1**. The thickness of bi-layer thin-film resistors increased with the increase of deposition time of Cr-Si thin films. No matter the Cr-Si thin films were used as the upper layer or lower layer, as the deposition time increased, the thickness of Cr-Si thin films had the value similar to that of single-layer shown in **Figure 1**.



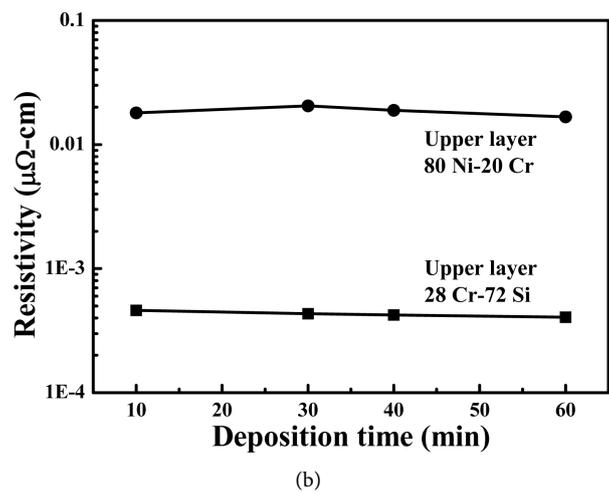
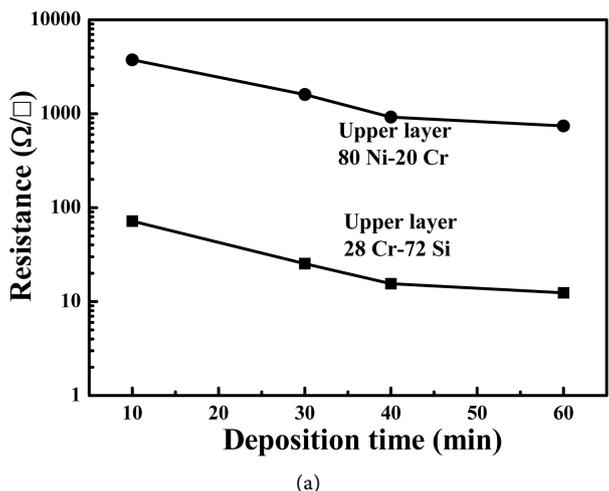
**Figure 5.** Cross section observations of the bi-layer thin-film resistors as a function of deposition time of Cr-Si thin films. 10 min-deposited Ni-Cr thin films as upper-layer and (a) 10 min-deposited or (b) 60 min-deposited Cr-Si thin films as lower layer; 10 min-deposited Ni-Cr thin films as lower-layer and (c) 10 min-deposited or (d) 60 min-deposited Cr-Si thin films as upper layer.



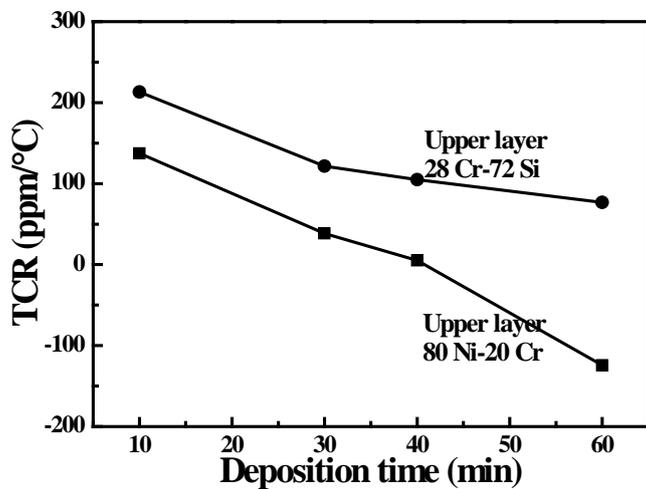
**Figure 6.** Variations in the thickness of the bi-layer thin-film resistors as a function of deposition time of Cr-Si thin films.

The bi-layer thin-film resistors' resistances were also recorded by the four-point measurement and the resistivity was derived from the resistances using a measurement of thin-film's thicknesses shown in **Figure 6**. The effect of deposition time of Cr-Si thin films on the variations of resistances and resistivity for the bi-layer thin-film resistors are shown in **Figure 7**. The results in **Figure 7** show two important conclusions, the first is that the resistance of bi-layer thin-film resistors decreases with the increase of the deposition time of Cr-Si thin films, and the second is that the resistivity of bi-layer thin-film resistors is almost unchanged as the deposition time (or thickness) of Cr-Si thin films increases. As Equation (1) shows, the resistivity can be calculated from  $R = \rho(A/l)$ . When the resistivity is almost unchanged as the deposition time of Cr-Si thin films increases, we believe that the decrease in the resistance of the bi-layer thin-film resistors is caused by the increase of thickness of Cr-Si thin films. The results in **Figure 7** shows that as the Ni-Cr thin films were used as upper layer and the Cr-Si thin films were used as lower layer (contact with the Ag electrode directly), the bi-layer thin-film resistors revealed the larger resistance (resistivity). Those results prove that as the bi-layer thin-film resistors are investigated, the contact material in the bi-layer structure is the most important factor to affect their electrical properties.

The variations in the TCR values of bi-layer thin-film resistors as a function of Cr-Si thin films' deposition time (thickness) were also measured, and the results are shown in **Figure 8**. **Figure 8** shows that the deposition time of Cr-Si thin films in the two different structures has large effect on the TCR values of bi-layer thin-film resistors. As the Cr-Si thin films were used as upper layer and their deposition time increased from 10 min to 60 min, the TCR value of the bi-layer thin-film resistors was decreased from 213.1 ppm/°C to 76.6 ppm/°C. Even the TCR value decreases with the increase of the thickness of Cr-Si thin films, the all measured results are still revealed the positive values. As the Ni-Cr thin films were used as upper layer and the deposition time of Cr-Si thin films increased from 10 min to 60 min, the TCR value of the bi-layer thin-film re-



**Figure 7.** Variations of (a) 25°C-measured resistance and (b) resistivity of bi-layer thin-film resistors as a function of deposition time of Cr-Si thin films.



**Figure 8.** Variations of temperature coefficient of resistance (TCR) values of the bi-layer thin-film resistors as a function of Cr-Si thin films' deposition time.

sistors was changed from 137.3 ppm/°C to -124.1 ppm/°C, which changes from the positive value to negative value as the thicknesses of Cr-Si thin films increase. As compared with the thickness of bi-layer structure shown in **Figure 7**, as the Cr-Si thin films were used as lower (upper) layer, their thickness increased from 54.5 (53.2) nm, 138.2 (141.5) nm, and 272.9 (284.5) nm, respectively. Those results in **Figure 8** prove that the thickness of Cr-Si thin films and the stacking method are the two reasons to affect the TCR values in the bi-layer thin-film resistors. **Figure 8** shows that as the 10 min-deposited Ni-Cr thin films were used as upper layer and the deposition time of Cr-Si thin films was 40 min, the TCR value was 5.2 ppm/°C, which is very close the 0 ppm/°C. The results in **Figure 8** also confirm our before conclusion, the contact material in the bi-layer structure is the most important factor to affect their electrical properties. The results in **Figure 8** also show a very important result. If we carefully control the thickness of the Cr-Si thin films, the bi-layer thin-film resistors can have a TCR value close 0 ppm/°C.

Nevertheless, many scattering effects are believed to affect the resistivity of bi-layer thin-film resistors, including surface scattering effect, grain boundaries (or interface) scattering effect, uneven or rough surfaces scattering effect, and impurities scattering effect, respectively [18]. Surface scattering effect is dependent on the thickness of thin-film resistors and other effects are dependent on the procedures and conditions used to fabricate the thin-film resistors, and thus, it is very difficult to quantify each of these effects without measurement [18]. In a thin-film material, as proposed, if the thin films have smooth or even surfaces, the surface scattering is believed as the main reason rather than other scatterings that will affect the electrical properties of thin-film materials. In this study, even the splitting is not really observed in **Figure 5**, the variations of TCR values are apparently influenced by the stacking method and thickness of Cr-Si thin films.

The lower layer is conducted with the Ag electrode, the ohmic conduction mechanism will dominate due to the contact between the lower layer materials (Ni-Cr or Cr-Si thin films) and Ag electrode. We believe that the interface layer exists between upper layer and lower layer thin-film materials, the interface scattering effect and rough surface scattering effect will happen between contact boundaries. The boundaries and the surface scattering became obvious and electrons' conduction between two thin-film materials will be limited. Some contact interfaces between the upper layer and lower layer are isolated completely, that carrier hopping conduction will dominate the electron motion owing to the discrete precipitates [19]. The two factors are believed as the reasons that the thickness of Cr-Si thin films and the stacking method will influence the TCR values of bi-layer thin-film resistors.

#### 4. Conclusion

As the deposition time increased from 10 min to 120 min, the thickness of Cr-Si thin films increased from 48.0 nm to 356.2 nm and the thickness of Ni-Cr thin films increased from 64.3 nm to 487.1 nm. As the deposition time was equal and less than 60

min, the thicknesses of Cr-Si and Ni-Cr thin films linearly increased with the increase of deposition time. As the deposition time increased from 10 min to 60 min, the TCR value of Cr-Si thin-film resistors was changed from  $-1467 \text{ ppm}/^{\circ}\text{C}$  to  $-1864 \text{ ppm}/^{\circ}\text{C}$  and the TCR value of Ni-Cr thin-film resistors was in the range of  $197 \text{ ppm}/^{\circ}\text{C}$  -  $230 \text{ ppm}/^{\circ}\text{C}$ , respectively. When the bi-layer thin-film resistors were deposited, the variations of TCR values were apparently influenced by the stacking method and thickness of Cr-Si thin films in the bi-layer thin-film resistors. As the deposition time of Cr-Si thin films in the bi-layer thin-film resistors increased from 10 min to 60 min, as Cr-Si thin films were used as upper (lower) layer, the TCR value was decreased from 213.1 (137.3)  $\text{ppm}/^{\circ}\text{C}$  to 76.6 ( $-124.1$ )  $\text{ppm}/^{\circ}\text{C}$ . As the 10 min-deposited Ni-Cr thin films were used as upper layer and the deposition time of Cr-Si thin films was 40 min, the TCR value was  $5.2 \text{ ppm}/^{\circ}\text{C}$ , which is very close the  $0 \text{ ppm}/^{\circ}\text{C}$ .

### Acknowledgements

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