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Co-sputtered Si–Cr resistive films

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Si–Cr films of variable composition between pure silicon and pure chromium have been deposited by co-sputtering on to glass substrates and thermally oxidized silicon wafers. In order to assess the applications of the Si–Cr films to thin film resistors, the electrical characteristics of the films have been determined as a function of composition, thickness, thermal treatments, etc.

1. Introduction

Si–Cr alloys are widely used as the base material in high-resistivity films for resistors and hybrid integrated circuit applications. The films are usually deposited by conventional flash evaporation or sputtering techniques, the starting material being of a fixed composition. Inherent to these techniques is the difficulty of obtaining films of different compositions, so that a limited range in the relative composition of silicon and chromium has been investigated [1, 2]. The co-sputtering technique offers unique advantages for obtaining a continuous variation of the Si/Cr ratio in the deposited films. However, no systematic studies have been carried out in order to assess the feasibility of this technique in the preparation of thin-film resistors. In this paper we present the results of the influence of composition on the electrical characteristics of the co-sputtered Si–Cr films. The thermal ageing of films with different compositions and thicknesses is also studied.

2. Experimental procedure

Si–Cr films with different relative compositions, between pure silicon and pure chromium, were deposited by co-sputtering in a Varian S-gun magnetron system. The system can hold up to three independent sputtering sources which are current controlled by d.c. power supplies of 7 kW. Silicon and chromium targets of 99.99% nominal purity were used in the experiments. The residual pressure of the system was lower than 1.3×10^{-4} Pa and the argon working pressure during the deposition was 3.2×10^{-1} Pa. Other experimental details are given elsewhere [3]. Prior to deposition, calibration experiments were made in order to determine the variation of the deposition rate of each material with the power applied to the source. For both the silicon and chromium targets this relation was linear. Films with different compositions were then obtained by fixing the power of the silicon source at 1.64 kW (current = 2 A) and varying the power of the chromium source between 0.12 and 1.62 kW (current between 0.42 and 3.12 A).

Cr–Si films in the form of rectangular strips of 31 mm × 2.2 mm were deposited either on to 7059 Corning Glass substrates or silicon wafers previously coated with an SiO_2 film, thermally grown. The silicon substrates were used in the ageing experiments at different temperatures up to 600° C. During deposition, the substrates were mounted on a fixed planetary system located about 30 cm from the sources which provides a thickness uniformity better than 3% in all the samples.

The resistance of the films and its temperature coefficient (TCR), in the range of 25 to 125° C, were measured using the four terminal configuration. The data were obtained by means of an HP digital multimeter, model 3455A, connected to a data acquisition system based on the HP 85 microcomputer. The film thicknesses were determined on a shadowed edge by a Talystep (Taylor and Hobson) with a resolution of ± 5 nm. The structure of the as-deposited samples was studied by X-ray diffraction techniques. Compositional analysis were also made by an X-ray microprobe attached to a scanning electron microscope.

3. Results and discussion

Table I reports some deposition parameters and the electrical characteristics of films with different compositions and a constant thickness of 250 nm. The theoretical composition was obtained from the measurements of the deposition rate of each separate source using the data of the bulk density of the corresponding material. As can be observed the theoretical composition agrees, within experimental error, with the results obtained by X-ray microprobe analysis. In all cases the as-deposited films were amorphous as detected by X-ray diffraction. In these films the sheet resistance decreases when the silicon content is decreased whereas the TCR presents a large dispersion between -100 and -800 p.p.m. K^{-1}. However, after annealing the films for 1 h at 250° C in air, the TCR becomes positive with values between $+350$ and $+510$ p.p.m. K^{-1} for most compositions. The large dispersion in the values of the TCR in the as-deposited films, can be attributed to the different texture in the as-deposited films [1]. Schiller *et al.* [4] have also shown that the deposition rate may play an important role in determining the TCR of the films. In

TABLE I Electrical characteristics of the Si–Cr films with different compositions (thickness, 250 nm)

Composition			Deposition rate ($nm\,sec^{-1}$)	Sheet resistance and TCR	
Theoretical		Microprobe at % Si		As-deposited R (Ω)	1 h at 250° C R (Ω)
Si/Cr	at % Si				
3/1	75	77	0.16	64.1	154.0
2/1	67	68	0.18	34.4	97.5
1/1	50	52	0.22	13.3	14.0
1/2	33	33	0.30	11.5	12.2
1/3	25	24	0.38	10.7	12.0

this regard, Fig. 1 illustrates the texture of the surface found in the as-deposited samples with different silicon contents. It is evident that the sputtering parameters, i.e. composition and deposition rate, seriously affect the surface texture of the films and hence the conduction mechanisms.

Fig. 2 presents the variation of the resistivity of the films as a function of the silicon content for samples with a constant thickness of about 250 nm. The films with a silicon content lower than 50 at % exhibit a resistivity practically independent of the composition (260 to 330 $\mu\Omega$ cm). Above 50 at % Si, the resistivity abruptly increases with the silicon content, the curve tending asymptotically towards the value found for pure silicon (3.7×10^4 $\mu\Omega$ cm, not represented in the figure). All the data published in the literature have been obtained from samples in this high range of the silicon content, showing a good agreement with the resistivity values given in Fig. 2 [2, 4, 5].

Samples with different composition were subjected to successive thermal treatments in air for 1 h at increasing temperatures. The effect of the thermal treatments on the sheet resistance of the films is shown in Fig. 3. The films with a low silicon content (Si $\lesssim$ 60 at %) show a good stability even at temperatures close to 400° C. Higher temperatures give rise to a fair increase in the sheet resistance. On the contrary, the samples with a silicon content higher than about 60% are extremely sensitive to the thermal treatments even at moderate temperatures (250° C). As noted above, this treatment also determines a large increase in the TCR as well. Both effects, the increase in the sheet resistance and in the TCR values, could be associated with the formation of a thin layer of silicon oxide at the inner boundaries of the grains within the films and a simultaneous incipient formation of $CrSi_2$ grains (see below) which might significantly contribute to the increase of the TCR [6].

Based on these results, further studies were also made on samples with 68% Si content. This material offers promising possibilities for the preparation of thin film resistors, because moderate thermal treatments of annealing can lead to a resistivity of 1000 $\mu\Omega$ cm. Table II summarizes the results obtained for the as-deposited samples with different thicknesses. A mean value of 775 $\mu\Omega$ cm is obtained for the resistivity with a dispersion of ± 5% in the whole thickness range. The TCR values are negative in all the samples within the range from -350 to -114 p.p.m.° C^{-1}. The effect of successive thermal treatments of 1 h in air at increasing temperatures is represented in Fig. 4. The sheet resistance again shows a good stability up to 200° C. However, higher temperatures produce an increase in the sheet resistance. This increase is much higher for the thinner films for which a greater effect of the above mentioned passivation layer is expected. The relative maxima of the sheet resistance observed in Fig. 4 can be attributed to the competitive effects of the thermal oxidation and the silicide formation which starts to appear above

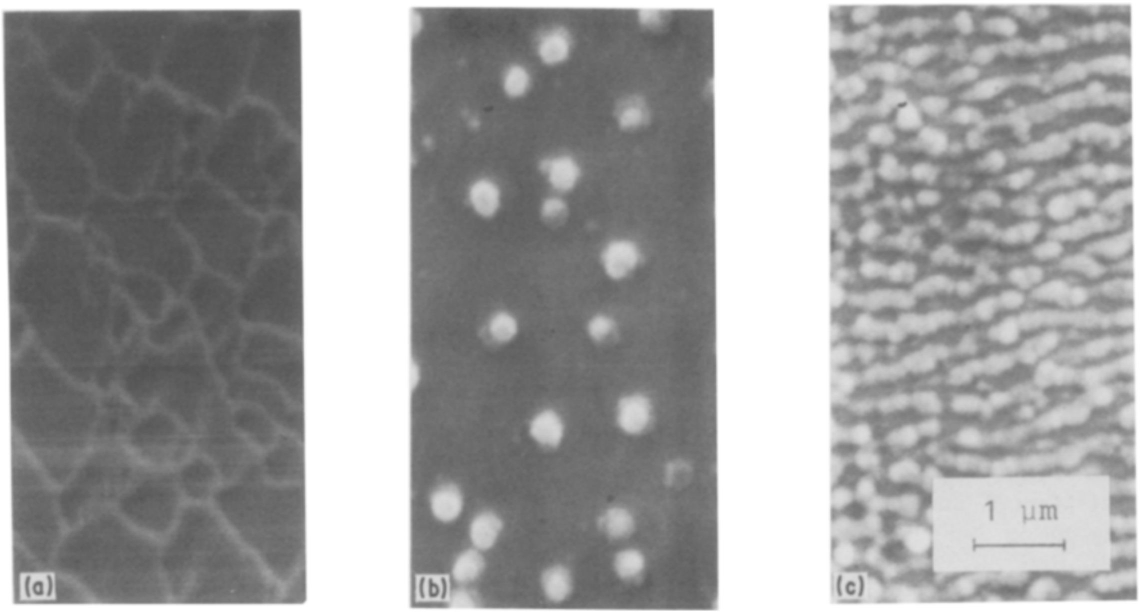

Figure 1 Scanning electron micrographs of the as-deposited films with different silicon content: (a) 67 at %, (b) 33 at %, (c) 25 at % Si.

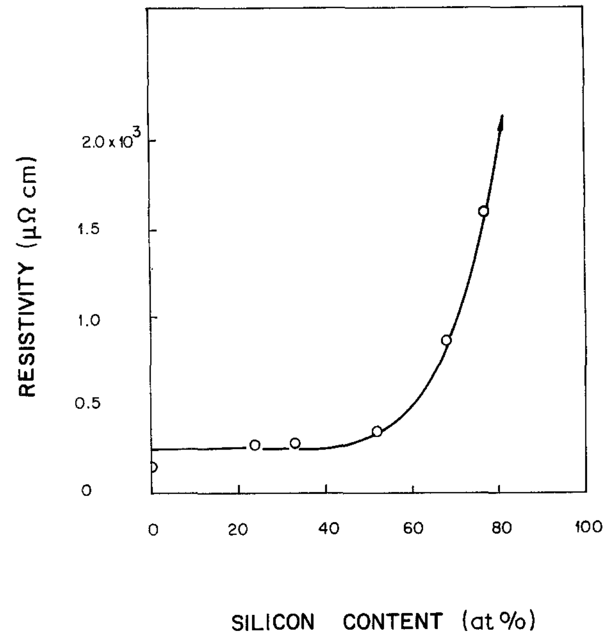

Figure 2 Variation of the resistivity as a function of the silicon content for films with a constant thickness of 250 nm.

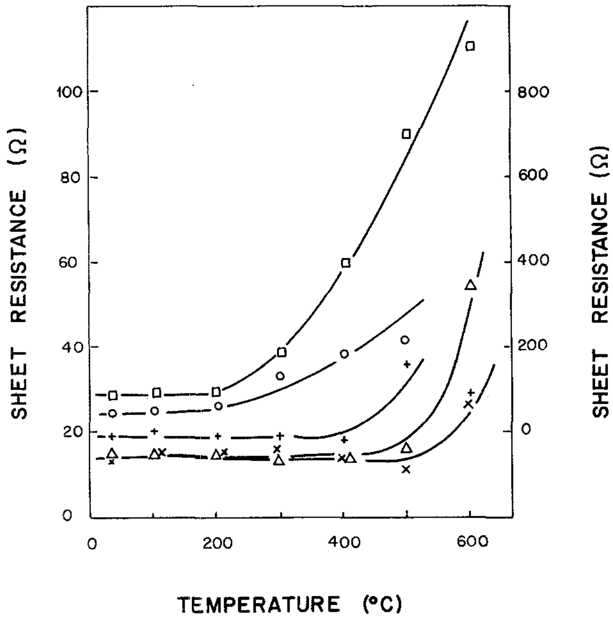

Figure 3 Variation of the sheet resistance as a function of the temperature of the thermal treatment for the Si–Cr samples with different silicon contents: right-hand axis (□) 78 at %, (○) 68 at % Si; left-hand axis (+) 58 at %, (△) 53 at %, (×) 25 at % Si.

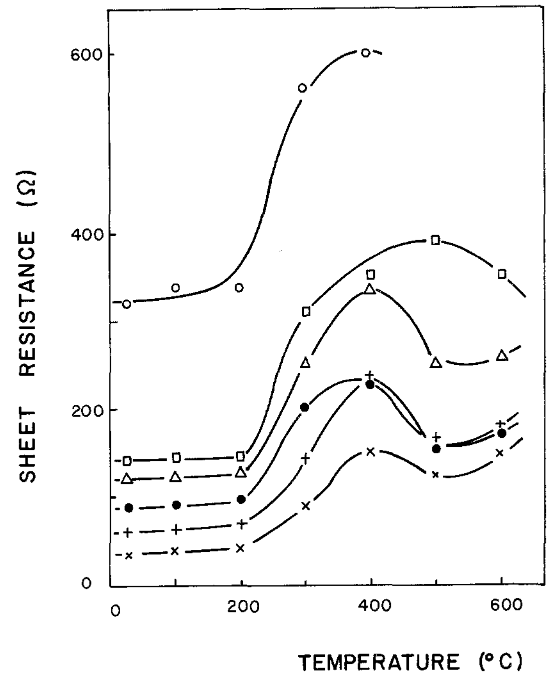

Figure 4 Variation of the sheet resistance as a function of the temperature of the thermal treatment for samples of 68% Si of different thickness: (○) 31.9 nm, (□) 74.3 nm, (△) 95.0 nm, (●) 127.4 nm, (+) 159.3 nm, (×) 212.3 nm.

this temperature, as detected by X-ray diffraction. Both the resistivity and the temperature coefficient (TCR $\cong$ 1500 to 3000 p.p.m.° C^{-1}) of the samples treated at temperatures higher than 300° C are characteristic of this compound [7, 8].

4. Conclusions

The co-sputtering technique has been evaluated as an alternative to the conventional flash evaporation or the sputtering from a single source to obtain Si–Cr films of variable composition. The as-deposited films with a low content of silicon (Si $\lesssim$ 50 at %) show a low resistivity ($\cong$ 300 $\mu\Omega$ cm) and negative values of the TCR. These films are stable under thermal treatments in air up to 400° C. The resistivity of the films richer in silicon (Si $\gtrsim$ 50 at %) is extremely dependent on the silicon content, increasing as the silicon content is increased. Films with a fixed composition corresponding to $CrSi_2$ have also been studied, showing good characteristics for application in thin-film resistors with high ohmic values.

TABLE II Electrical characteristics of $CrSi_2$ films (68% Si content) of different thickness

Deposition time (min)	Nominal thickness (nm)	Sheet resistance (Ω)	Resistivity ($\mu\Omega$ cm)	TCR (p.p.m.° C^{-1})
3	31.9	244.7	780.6	−344
5	53.1	145.2	770.8	−243
7	74.3	105.8	786.0	−280
8	84.9	90.7	770.0	−124
9	95.0	85.4	816.4	−318
10	106.2	71.3	757.6	−232
12	127.4	63.2	804.7	−280
15	159.3	49.9	705.3	−202
20	212.3	35.6	755.5	−199
30	318.5	25.3	806.4	−114

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