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High stability nano-multilayer resistive films

Arunas Andziulis*, Beatrice Andziuliene, Jonas Vaupsas, Marius Zadvydas

Department of Informatics Engineering and Physics, Klaipeda University, Bijunu 17, Klaipeda, LT-91225, Lithuania

Abstract

The results of deposition and following research of nano-multilayer resistive films, provided for the high long-term stability resistors, distinguishing by temperature coefficient of resistance (TCR) around zero and necessitate negative value, and made by using classical Cr–Ni–Si material, are presented in this work. This multilayer structure consists of 3–8 nm resistive layers and 1–2 nm sliced barrier–insulator layers spaced each between another for preventing the vertical coalescence of metal grains. Resistive thin films were deposited by using magnetron sputtering and after it the barrier–insulator layers were formed by plasma-assisted oxidation of segregated silicon. Composition and thickness of the resistive layer was chosen in such a way as after the magnetron sputtering from Cr–Ni–Si (54–06–40 w/w %) alloy target, we would have enough of silicon necessary to form the Si-amorphous matrix and barrier layer as well. However, there should be not overmuch of metals Cr and Ni to avoid the intergrowth of Cr–Ni nano-grain precipitates, which should not form the metal predicted conductivity after annealing. Experimental results show that multilayer system of two or three resistive layers having sheet resistivity $R_S = 300–550$ Ω/sq. can ensure the TCR in a range from ±2 ppm K^{-1} up to the negative value of −60 ppm K^{-1}. The long-term stability of these nano-multilayer films is $\Delta R/R$ ($t = 1000$ h, $T_{st} = 358$ K) ≤ 100 ppm.

Keywords: Nano-multilayer; Long-term stability; Resistive films; TCR

1. Introduction

Classic nanocomposite thin resistive films, based on Ni–Cr with the embed silicon or without it and deposited with appliance of diode, triode or magnetron sputtering onto mono-Si wafer, ceramic or other substrates, after annealing in air provides a high long-term stability of the Ni–Cr–Si one-layer films. Results of present and some other researches show that in a specified range of film composition (20–41 at.% of Cr, 4–20 at.% of Ni and 50–75 at.% of Si) the temperature coefficient of resistance (TCR) has values close to zero [1]. In these cases, the variation of long-term stability, expressed as a ratio $\Delta R/R_i(t_{st})$ of thin film resistor (TFR), during the ageing under conditions of $t_{st} = 1000$ h at temperature $T_{st} = 358$ K, did not exceed 1% [2,3]. However, the results of the proposed new technology should give the required ratio of $\Delta R_i/R_i(t_{st}) < 0.1\%$, which can be achieved by using various resistive composites and by applying annealing on purpose to get the concrete sheet resistance (R_S) and necessary TCR of thin film [4].

In general, one-layer thin film resistors (Fig. 1) with the pre-defined R_S, TCR and $\Delta R/R(t_{st})$ are being realized by mathematical modeling of sputtering method and annealing treatment regime predicted by theory of conductivity of growing metal nano-grain precipitates in amorphous matrix [5]. The greater thickness d_R of resistive layers ensures a better durability of TFR against various negative factors in process of integrated circuit technology and gives the higher long-term stability in case of the biggest values of dissipation power. Also the highest long-term stability $\Delta R/R(t_{st})$ and pre-defined R_S of thin film resistor also are being realized by anodizing or plasma-assisted oxidation the surface of resistive thin film.

Metal grain growth onto substrate, formulated by Gibson and Thomson, and the subsequent coalescence and Oswald ripening process, which are going on in as-deposited nanocomposite thin film, can be expressed as the function depending on thickness of resistive layer d_{R0} and on regime of annealing [6]. That is why the increasing of annealing temperature and duration causes the miniaturization of space Δx_g between grains up to their intergrowth and fusion, which, in turn, leads to the metal

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* Corresponding author.
E-mail address: arunas.andziulis@ik.ku.lt (A. Andziulis).

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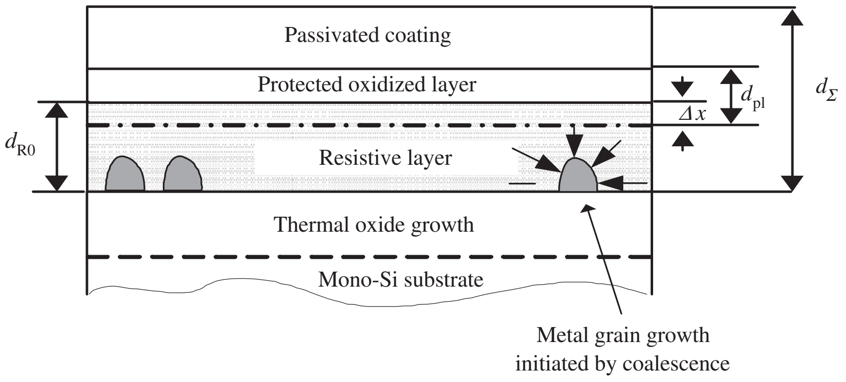

Fig. 1. One-layer laser trimmed nanocomposite thin film resistor with protective oxidized and passivated layers of silicone monomers: d_{R0}—thickness of as-deposited resistive layer; d_{pl}—thickness of protected layer grown by plasma-assisted oxidation; Δx—depth of oxidation into intergrain spacing; d_Σ—summarized thickness of resistive multilayer film.

predicted conductivity with the undesired and typically high positive TCR.

Therefore, on purpose to increase a resistance R_S by working out the thicker film, we have to rise the specific resistivity of film by oxidation or by nitridation on the amorphous semiconductor matrix and by synthesizing the nanocomposite thin film in advanced but more complicated process carried out by using the radio frequency plasma-assisted magnetron sputtering apparatus in oxygen or nitrogen ambient.

The aim of this work is the deposition and subsequent research of nano-multilayer resistive thin film ($d_R < 20$ nm) with the barrier–insulator layers, which should prevent the vertical coalescence of metal grains in the film provided for high long-term stability ($\Delta R/R(t_{st})$) resistors with a purpose to achieve the pre-defined sheet resistance (R_S) and temperature coefficient of resistance around to zero or desired negative value by using classical nanocomposite Cr–Ni–Si material.

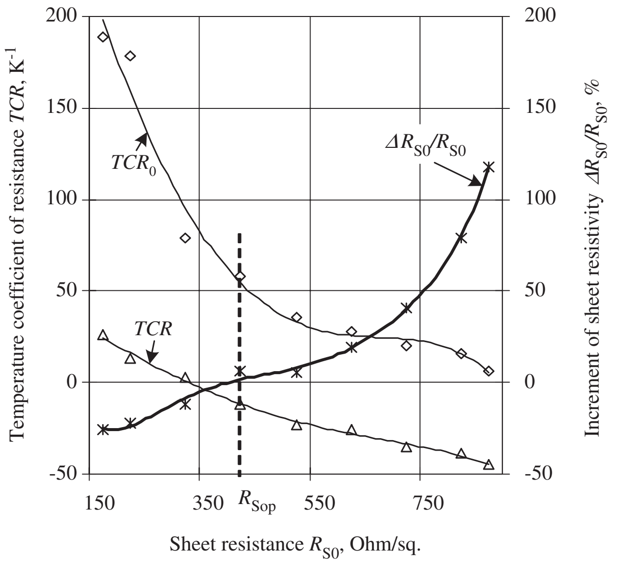

Fig. 2. Temperature coefficient of resistance of film with (TCR) and without (TCR_0) pre-annealing and the final sheet resistivity ($\Delta R_{S0}/R_{S0}$) as a functions of as-deposited sheet resistance (R_{S0}) of one-layer ternary Cr–Ni–Si alloy; R_{S0p}—sheet resistance at meta-inverse point of stability.

2. Experimental details

Films used for experimental researches were worked out by sputtering from ternary Cr–Ni–Si alloy target having structure of 20–41 at.% of Cr, 4–7 at.% of Ni and 50–75 at.% of Si, while the oxidized mono-Si wafer was used as a substrate [7]. The samples were annealed in air atmosphere during $t_{an} \geq 2$ h at $T_{an} = 623$ K. Microstructure of film and oxide layer were analyzed by X-ray diffraction and plan-view transmission electron microscopy while the thickness of film and oxide layer were monitored in scale by means of nano-interferometry and backscattering spectroscopy [8,9].

In case of the proposed method, the plasma-assisted process is the mostly expedient as it meets the relevant requirements of this technology. Such process guarantees a sufficiently low temperature of substrates ($T_a < 250$ °C) during the plasma-assisted technology and does not activate a new significant coalescence of metal precipitates. So, the film structure can be destroyed by electromagnetic radiation, which penetrates into full depth of film which accelerates the dissolution of the oxygen (or nitrogen) ions that increases the surface oxidation (or nitridation) of thin film [10].

3. Results and discussion

Experimentally researched magnetron sputtering from Cr–Ni–Si target of various composition revealed that in case of one-layer film, formed onto thermally oxidized mono-Si wafer, the desired high long-term stability can be achieved only when the ternary Cr–Ni–Si alloy has a composition corresponding to ratio 54–06–40 w/w % (40.5–4.0–55.5 at.%). This composition of annealed one-layer film distinguishes by relatively low values of ratio $\Delta R_S/R_{S0} < \pm 7\%$ and by TCR $\approx +20\ldots+70$ K^{-1} in a range of sheet resistivity of $R_{S0} \approx 300$–550 Ω/sq. The reached thickness of these films, as defined by mentioned methods, was about 12 nm with $R_{S0} \approx 500$ Ω/sq. In turn, the XRD and TEM analysis indicated that the resistive layer, having the homogeneously distributed Cr–Ni grains in near-amorphous Si-phase and discerning by semiconductor conductivity, has been developed in the thin film of selected ternary alloy but after pre-annealing in air atmosphere during $t_{an} \geq 2$ h at $T_{an} = 623$ K.