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TiN_x THIN-FILM RESISTORS FOR HYBRID INTEGRATED CIRCUITS

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TiN_x thin-films have been evaluated for use as thin-film resistors. Thin-films were obtained by reactive triode sputtering of titanium in nitrogen atmosphere on crystallized glass substrates. In the resistive TiN_x layers, the value of x was 0.96.[2] The value of the sheet resistance of the tested layers was 30 ohm/sq. Stability and TCR were measured during accelerated ageing.

1. INTRODUCTION

TiN_x is a resistor material whose application in microelectronics deserves attention. Nitrogen displays a large range of solubility in T_i, and if this range is exceeded it forms compounds of metallic properties. Hence, it may be inferred that for TiN_x near the phase boundary ($Ti\alpha$ + N) → TiN (as for TaN), both the resistivity and TCR have a low sensitivity to doping. The increase of critical temperature for $Ti\alpha \rightarrow Ti\beta$ occurring with the increasing nitrogen doping implies high stability of resistance.

2. PREPARATION OF RESISTORS

The TiN_x films were d.c. triode sputtered from a titanium target in a mixed argon-nitrogen atmosphere. The total argon-nitrogen pressure was 6.6×10^{-2} Pa and residual gas pressure was 2.6×10^{-4} Pa. The crystalline glass substrates were heated up to 473 K. The partial nitrogen pressure changed from 1.3×10^{-3} Pa to 2.6×10^{-2} Pa corresponding to nitrogen content of 2% to 40% in the gas mixture. The negative voltage of the target was changed from 400 V to 1 kV. The variations in reactive gas pressure and target voltage were accompanied by variations in deposition rate, affecting the resistivity and TCR of TiN_x films.

3. STABILITY OF RESISTANCE

3.1. *Resistors not Preliminarily Aged*

Thermal ageing stability of resistance was measured as a function of sputtering parameters at temperatures ranging from 423 K to 573 K. Figure 1 shows the

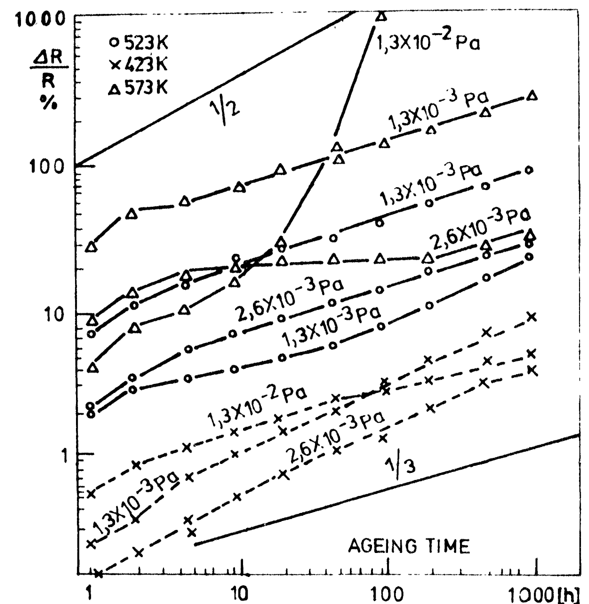

FIGURE 1 Oven-ageing curves of titanium nitride, nitrogen pressure and ageing temperature being the parameters.

resistance changes for resistors manufactured at various nitrogen pressures and oven-ageing temperatures of 423 K, 523 K and 573 K. It has been observed that the resistance starts to rise during the first hours of ageing.

The highly doped resistors aged at 573 K have special properties. The resistance of these resistors increases rapidly to infinity, and the colour of the resistance layers changes. This was probably connected with the formation of TiO_2.

At the oven-ageing temperature of 423 K, the highest stability was displayed by the resistors manufactured at 2.6×10^{-3} Pa, 3.3×10^{-3} Pa and 4×10^{-3} Pa. The curves plotted for this nitrogen pressure (in Figure 1 only the curve for 2.6×10^{-3} Pa has been shown) are parallel and on a log-log plot have a slope of about 1/2.

Figure 2 shows the plot of log $\Delta R/R$ as a function of $1/T$ which has been obtained from the data given in Figure 1. Assuming the parabolic oxidation is low, the calculated thermal activation energy was 0.59 eV or 13.6 kcal per mol. Similar results have been obtained by Das and Osadnik[1] for reactively evaporated TiN_x layers and by Berry, Hall and Harris[3] for TaN. The increase of target voltage from 400 V to 1 kV and of substrate temperature from 473 K to 573 K during the deposition process have small beneficial influence on the stability. It appears that stability depends on the thickness of resistance layers, being higher in thicker layers. A typical example is shown in Figure 3.

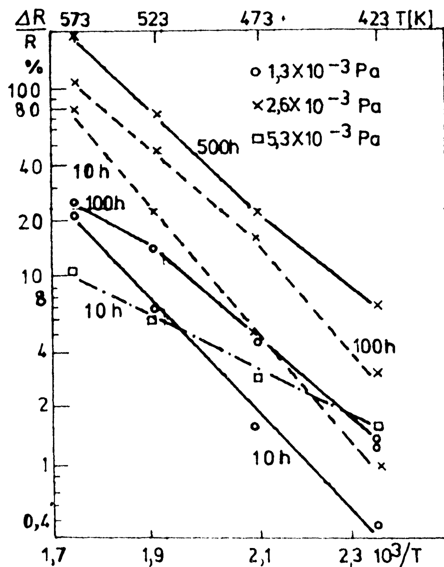

FIGURE 2 $\Delta R/R = f(1000/T)$ for various nitrogen pressures and oven-ageing time.

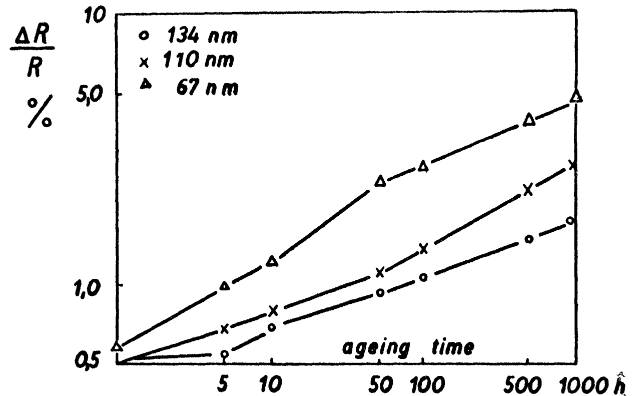

FIGURE 3 Oven-ageing curves with thickness of resistance layer as a parameter.

3.2. *Prestabilized Resistors*

Some of the resistors manufactured at a nitrogen pressure of 2.6×10^{-3} Pa and substrate temperature of 473 K were prestabilized at 523 K or 573 K. Preageing time varied from 0.5 h to 50 h.

Figure 4 shows the changes in resistance of prestabilized resistors with a sheet resistivity of 30 ohm/sq after 1000 h oven-ageing at 423 K. It has been found that the stability of resistors prestabilized at 523 K or 573 K was similar, if preageing time was longer than 5 h. In this case the changes of resistance were below 0.2%.

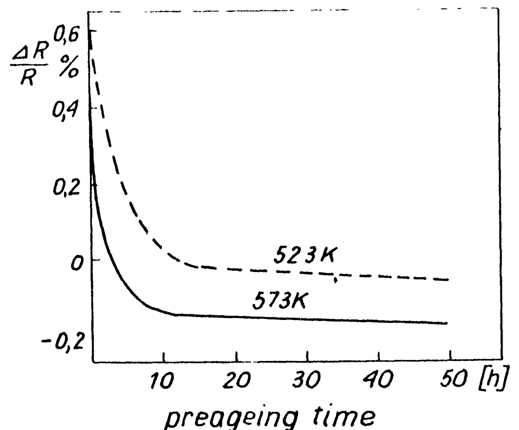

FIGURE 4 Resistance changes after 423 K, 1000 h test as a function of preageing time for preageing temperatures of 523 K and 573 K.

4. TEMPERATURE COEFFICIENT OF RESISTANCE

The TCR of TiN_x thin-film resistors strongly depends on nitrogen pressure. This dependence is depicted in Figure 5. Resistors manufactured at the pressure of 2.6×10^{-3} Pa displayed special features, the TCR being negative and close to zero. The TCR of TiN_x resistors was practically independent of the thickness of the resistance layers if their structure remained unchanged. If TCR < 0, its absolute value increases and if TCR > 0, its absolute value decreases during the oven-ageing (Figure 6). In resistors produced at a pressure higher than 4×10^{-3} Pa, the ageing time weakly affects the TCR value, being strongly dependent at a temperature of 573 K. In all the resistors obtained at 2.6×10^{-3} Pa and processed at 523 K for 5 hours, the value of TCR after 1000 h ageing at 423 K ranged between –8 ppm/K and –36 ppm/K.

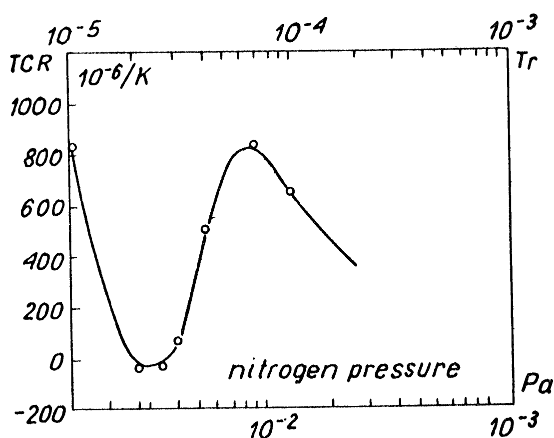

FIGURE 5 TCR versus nitrogen pressure.

5. CONCLUSION

By analysing the TiN_x thin-film sputtered resistors, it has been found that resistors produced at a nitrogen pressure of 2.6×10^{-3} Pa, substrate temperature of 473 K and target voltage of 400 V had the best TCR, the highest stability and the maximum value of the resistivity (216 μohm . cm).

In non-prestabilized resistors with sheet resistances ranging from 20 ohm/sq to 40 ohm/sq, subject to 1000 h oven-ageing at 423 K, the mean value of $\Delta R/R$ was 3.5%, and the mean value of TCR was –35 ppm/K.

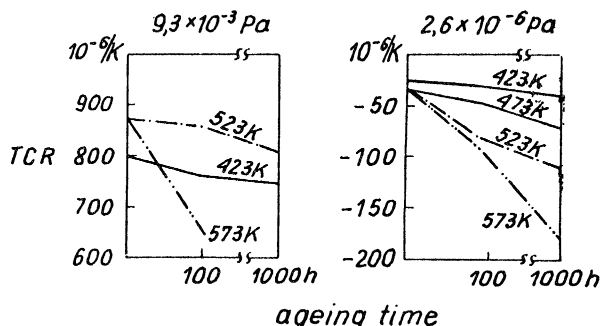

FIGURE 6 TCR versus ageing time for various ageing temperatures and nitrogen pressures.

Standard temperature treatment at 523 K for 5 h causes the mean value of $\Delta R/R$ to be reduced to 0.2% and that of the TCR to –22 ppm/K. It should be emphasized that for reactively evaporated TiN_x resistors tested under the same conditions, the value of $\Delta R/R$ and TCR, obtained by the authors of this paper, were 0.35% and –72 ppm/K, respectively.

The X-ray diffraction patterns of TiN_x film (thickness 2000 Å) deposited at nitrogen pressure 2.6×10^{-3} Pa and deposition rate 1.6 Å/s have shown titanium nitride structure of NaCl type. Thus, these films were strongly oriented in the [1 1 1] direction, perpendicular to the glass substrate. The evaluated lattice constant was 4.18 Å showing the deficiency of nitrogen and presence of impurities.

Considering the form of the resistance changes, the value of activation energy and the weak dependence of TCR on the ageing time, it may be assumed that oxydation across the surface oxide layer is probably the principal ageing mechanism.

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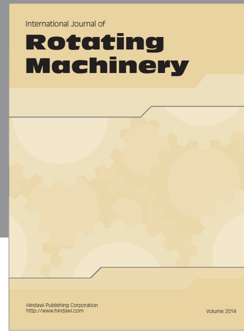
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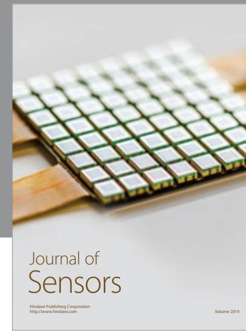
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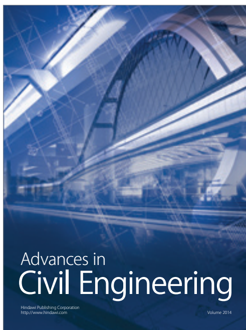
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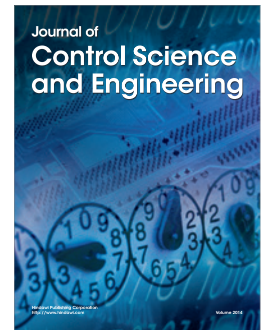
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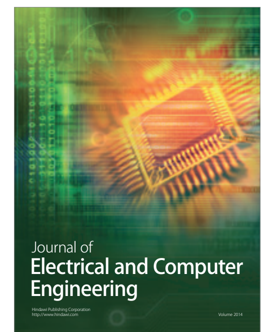
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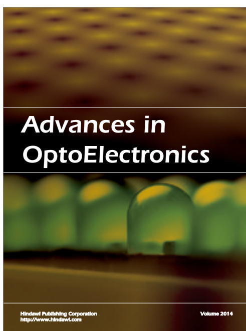
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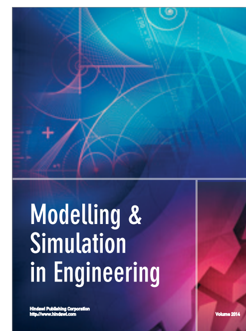
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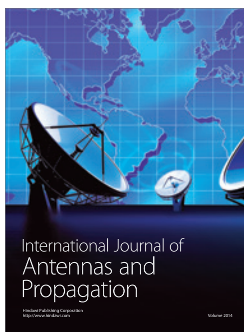
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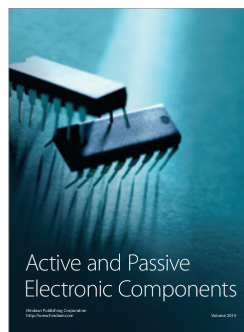
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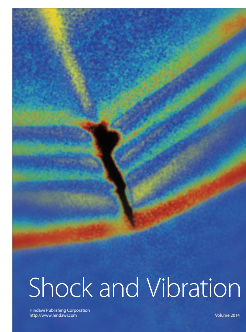
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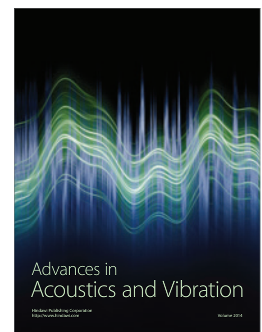
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