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Reliability and characteristics of magnetron sputter deposited tantalum nitride for thin film resistors

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A B S T R A C T

Tantalum nitride (TaN) films were deposited onto SiO_2/Si and multilayer ceramic (MLC) substrates with a reactive direct current magnetron sputtering method. After they were kept at different N_2 partial pressures and substrate temperatures, these were characterized for their electrical, structural, and mechanical properties for use as thin film resistors (TFRs). Results of X-ray diffraction analysis, observation of microstructure, sheet resistance measurement, and accelerated degradation tests highly indicated that TaN films with high crystalline phases, good surface roughness, stable deposition rates, appropriate sheet resistances, and high reliabilities could be obtained if N_2 partial pressure was maintained at around 20%. Adhesive strengths of TaN films grown on MLC substrates were increased with increasing substrate temperature up to 300 °C. A low resistance change was confirmed by temperature coefficient of resistance variation as a function of temperature, implying high reliability and durability. Results of this study suggest that TFRs described in this study are suitable for embedded passive resistors with practical applications, including controlled resistances for fabricated TaN based TFRs with different widths.

1. Introduction

Rapid growth of modern electronics industries has increased the requirement for miniaturization and integration of electronic devices to meet and satisfy consumer demands globally. To fulfill these requirements, there has been an increase in general use of integrated circuit technologies regionally and around the world. Among various types of passive components, tantalum nitride (TaN) films are considered the most promising candidates for embedded passive resistors [1–3] in integrated circuits due to their outstanding properties such as excellent corrosion resistances, hard materials, chemically inert features, high strengths and toughness even at elevated temperatures, histocompatibility, high conductivities, and thermal stabilities [4–8]. For these reasons, TaN films are implemented as robust materials of choice for a wide range of applications such as diffusion barriers [9,10], wear and corrosion-resistance materials [11], high-speed thermal printing heads [12], stable resistors used in Si-based integrated circuits [13–15], pressure sensors [16,17], and microelectronic industries.

TaN films have been deposited using physical and chemical vapor deposition techniques [4,5,14,18–20]. Of available techniques, sputtering is an attractive method to deposit TaN films because tantalum is a refractory metal with a high melting point. Sputtering can also be easily scaled up from laboratory-sized targets to large-scale industrial applications. Therefore, many studies on film preparation of TaN have mostly focused on properties of films, e.g., microstructures and electrical resistivity depending on deposition conditions. To ensure enhanced performance and reliability of TaN films, studies on durability and reliability as well as on physical and electrical properties of TaN films should also be investigated by researchers to identify viable properties of TaN films.

This study had two objectives: 1) to determine the influence of nitrogen partial pressure on electrical and microstructural properties of direct current (DC) magnetron sputter-deposited TaN films and examine relationships among change of crystalline structures, surface morphology, and electrical resistivity; and 2) to investigate the reliability of prepared TaN films. To determine the influence of nitrogen partial pressure on the stability of TaN films in a high-temperature environment, accelerated degradation test (ADT) such as thermal shock

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cycling was performed and the electrical resistance changes of TaN films as a function of degradation cycling number were investigated. To enhance the durability of TaN films, the substrate was heated and adhesive strength and temperature coefficient resistance (TCR) of TaN films grown at different deposition temperatures were determined. Finally, for practical purposes, we fabricated TaN thin film resistors (TFRs) and evaluated their resistances for application as embedded passive resistors.

2. Experimental details

All TaN films were deposited using a reactive DC magnetron sputtering system with a 4 in-diameter metallic Ta target. SiO_2/Si and multilayer ceramic (MLC) was applied as substrate material which was well cleaned with acetone, isopropanol, and deionized water. Argon and nitrogen with purities of 99.999% were used as carrier gas and reactive gas, respectively, for film deposition. During deposition, the substrate stage was rotated at 10 rpm to obtain a homogeneous film quality and thickness. The system was first pumped to 2.67×10^{-4} Pa in about 5 h. Then a mixture of pure Ar/N_2 gases was pumped into the deposition chamber by using a mass-flow controller. While maintaining working pressure at 1.33×10^{-1} Pa, partial pressure of N_2 was varied from 10% to 40% (N_2 / (N_2 + Ar)). Target-to-substrate distance was about 6 cm. SiO_2/Si substrates were not heated while MLC substrates were heated up to 300 °C in about 6 h to enhance the adhesive strength between the substrate and films. Detailed sputtering conditions are summarized in Table 1. To confirm resistance changes depending on widths of TaN films, TaN TFRs with Au electrodes were fabricated by photolithography with a lift-off process on 4-in. MLC substrates. Fabrication procedures of TFRs are shown in Fig. 1.

Phase composition and crystalline structure were investigated by X-ray diffraction (XRD, X'pert PRO, Panalytical) spectra at a glancing angle of 1°, scanning from 20° to 80°. All spectra were collected using Cu K_α band at 40 kV and 30 mA. Thickness and microstructure of films were determined by field emission scanning electron microscopy (FE-SEM, S-4700, Hitachi) with operating voltages of 5 to 15 kV. Film roughness, R_{rms}, was determined by atomic force microscopy (AFM, PSIA, XE-100). Sheet resistances of TaN films were measured with a 4-point probe system (Mitsubishi Chemical Corporation, Loresta-GP MCP-T600). Resistivity of TaN was calculated from resistance. To study the effect of high temperature on stability of TaN films, environmental test was carried out in an environmental test chamber (Challenge 250, ACS). Thermal shock tests of TaN films were performed in a thermal cycling chamber (TSA-41L, TABAI ESPEC). Temperature profile in the thermal cycling test was measured by varying the temperature from −20 °C to 100 °C with monitored 30 min dwell times at both applicable temperature extremes. Sheet resistances of TaN films under thermal shock were measured using a 4-point probe system. Adhesive strength between TaN film and MLC substrate was measured using a universal testing machine (DUT-300CM, Daekyung Engineering Corp., Korea) at a loading speed of 5 mm/min. A force-displacement curve was derived from the tensile test and the adhesive strength F of TaN films was estimated using the following equation: $F = |f_{max}|/A$, where f_{max} was the measured peak load value of the breaking force and A was the area that the TaN film was peeled off. TCR values of TaN films and substrate heated TaN films were calculated with the following equation: TCR (ppm/°C) = $(R_m - R_o) / R_o \times (1 / \Delta T) \times 10^6$, where R and R_o were resistivities of film at measured temperature and room temperature (RT), respectively, and ΔT was difference between measured temperature and RT [21].

Table 1
Experimental parameters and conditions of prepared TaN films.

Parameters	Conditions
Sputter type	Magnetron
Power	DC 700 W
Target	Tantalum
Carrier gas	Ar
Reactive gas	N_2
Substrate rotation	10 rpm
Substrate temperature	Room temperature, 150 °C, 300 °C
Base pressure	2.67×10^{-4} Pa
Working pressure	1.33×10^{-1} Pa
Substrate pre etching	Ar plasma
Total gas volume	40 sccm
N_2 partial pressure ratio	10, 20, 30, 40%

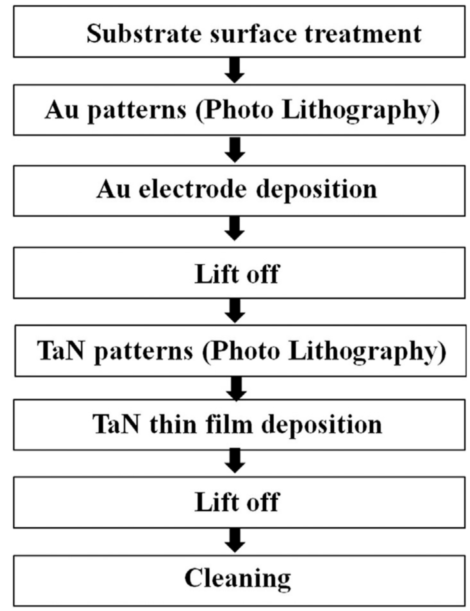

Fig. 1. Fabrication procedures of TaN based TFRs with Au electrodes.

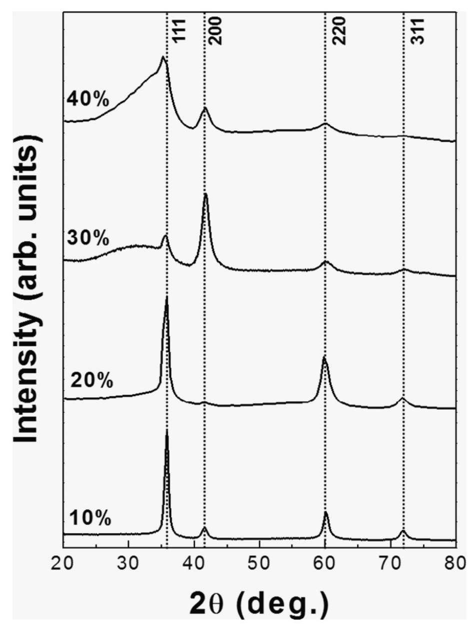

Fig. 2. X-ray diffraction patterns of TaN films deposited onto SiO_2/Si substrate under N_2/Ar processing gas with different N_2 partial pressures (10, 20, 30, and 40%).