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Fabrication of a low resistivity tantalum nitride thin film

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Abstract

Novel bilayer TaN film has been developed using reactive ion DC sputtering. The film has a low resistivity of ~80 μΩ-cm and is more stable compared with high resistivity films with high nitrogen flow rates. Low angle X-ray diffraction results show that the low resistivity TaN film is highly crystallized than that of each individual film deposited in the bilayer design. The crystalline structure and the film resistivity of the bilayer TaN film remain unchanged even when the thickness of each layer is changed, indicating large process window, that is critical for high volume manufacturing.

Keywords: TaN; Thin film resistor; DC sputtering; Barrier layer; Glancing angle XRD

1. Introduction

Tantalum nitride (TaN) has been used effectively in semiconductor industry because of its high melting point, good resistivity uniformity, low temperature coefficient of resistivity (TCR), low voltage coefficient of resistivity (VCR), good thermal stability, good selectivity to chemical mechanical polishing (CMP), and good barrier properties in Cu interconnects. Although TaN deposition process can be tuned to achieve wide range of electrical properties by varying the film stoichiometry [1–8], as one of the barriers for copper back end-of-line (BEOL) processing, high resistivity and narrow process window continue to limit the usability of these films as thin film resistors in Silicon IC manufacturing.

TaN has good adhesion to GaAs [9,10] and has been used as thin film resistors in the fabrication of power amplifiers [11]. Reported resistivity value of DC-sputtered TaN thin film ranges from 200 to 1000 μΩ-cm [8,12]. It has long been proven that grain boundaries are the most important diffusion paths for the polycrystalline TaN films [13–16]. Several attempts were made in altering the stoichiometry of TaN_x films and change their grain boundary density [17–19]. Changes in the barrier properties will not only affect copper diffusion along copper/barrier interface, but also affect the grain size and crystallographic orientation of the copper, which will also in turn affect the reliability of the interconnects. TaN_x, with $x > 0.5$ has the lowest grain boundary density thus the leakage between transmission lines is the lowest compared to tantalum film, and tantalum-rich TaN_x ($x < 0.5$) films [19]. However, with increased nitrogen flow in DC sputtering, the nitrogen content in the TaN film also increases along with rapid increase in resistivity.

In this paper, a low resistivity TaN film fabricated by DC reactive ion sputtering will be discussed. A novel double layer (bilayer) TaN thin film scheme is developed for the first time, and is shown to be highly oriented, crystalline, large grain size, as well as significantly reduced bulk resistivity.

2. Experimental

Reactive ion sputtering was performed in a Balzer LLS502 sputter system, with DC power, tantalum target, and independently controlled N_2 and Ar gas flows. GaAs mechanical wafers were used as substrates. To obtain the

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bilayer film, a thin TaN seed layer was deposited on GaAs (first layer), followed by the deposition of a thick TaN layer (second layer) without breaking the vacuum. The first layer was deposited using low DC power, with N_2/Ar ratio of 10%. The second layer was deposited with higher DC power, with N_2/Ar ratio of 1.2%. The base pressure for both processes was kept the same and was controlled by a throttle valve in the system. Film stress was obtained by measuring the wafer bow, before and after the film deposition, by using a laser film stress measurement (FSM) tool. Thickness was measured using both cross-section Scanning Electron Microscope (SEM) and a profilometer. Sheet resistance was measured using 4-point probe technique. Glancing angle X-ray diffraction (XRD) spectra at a glancing angle of 1°, scanning from 20° to 80°, were collected to determine the crystalline orientations of the single and bilayer thin films. All the spectra were collected using Cu K_α band at 45 kV, 40 mA.

3. Results and Discussions

In reactive ion DC sputtering, Ar ions strike the Ta target and resultant Ta ions will come out into the plasma phase. In the plasma mixture the tantalum ions will react with nitrogen ions to form TaN compounds which will in turn deposit onto the substrate surface to form TaN thin film. At low DC power, which transpires to a low Ta ionization rate, combined with high N_2/Ar ratio in the plasma mixture, the TaN reaction is thermodynamically controlled. Fig. 1 shows the XRD spectrum of TaN film that was deposited at low DC power and 10% N_2/Ar ratio. The thickness of this film is 190 Å with a compressive stress of −4000 MPa, and its resistivity is over 480 μΩ-cm. This TaN film is polycrystallized with a 7.18% N content. There are many different crystalline orientations, TaN (1 1 1), TaN (2 0 0), TaN (2 2 0), and TaN (3 1 1), as shown in Table 1. The average grain size of this film is estimated to be around 40 Å, using Scherrer's Formula, given in Eq. (1)

$$d = \frac{0.9 \times \lambda}{b \cos \theta}, \tag{1}$$

where d is the grain size, λ is the X-ray wavelength, b is the peak's full-width at half-maximum (FWHM), and θ is the peak position angle (2θ divided by 2). With such small grain size the grain boundary density in the film is much higher and the chance of copper diffusion along grain boundary is very high.

On the other hand, high DC sputtering power will increase the ionization rate of tantalum. At 1.2% N_2/Ar ratio, the nitrogen is in deficit, the total reaction becomes more dynamically controlled. Fig. 2 is the XRD spectrum of a TaN film deposited with high DC power and low N_2/Ar ratio. The total thickness of this film is 750 Å with a compressive stress of −900 MPa, and its resistivity is 154 μΩ-cm. Instead of TaN polycrystalline structure in the high resistivity film, this film has a single crystalline phase of $TaN_{0.1}$, which has 10% nitrogen in the film. Another identification peak of this crystalline phase shows up at 68.38° (2θ), which is the (2 1 1) orientation of this body-centered cubic (BCC) structure of $TaN_{0.1}$. This indicates that even at a deficit N_2/Ar flow in the sputtering gas the nitrogen content in the film is actually increased due to the high sputtering power and increased tantalum ionization. This film is also highly crystallized along its (1 1 0) plane for the intensity of X-ray diffraction is much higher compared to the previous film. The FWHM at 37.74° (2θ) is 2.71°, which translates to a grain size of 30 Å, and is smaller than the high resistivity film. Copper diffusion can be expected even faster in this film because of more grain boundaries formed by smaller crystalline. The (1 1 0) peak in Fig. 2 is not a well-defined Gaussian peak.

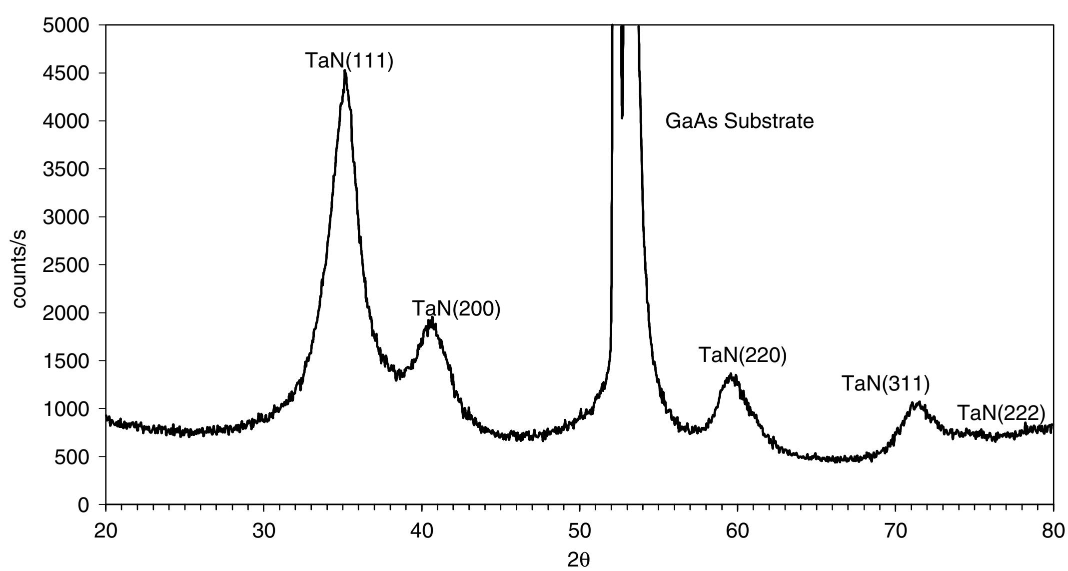

Fig. 1. Glancing angle XRD pattern of the high resistivity TaN film on GaAs.