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Full Length Article

Electrical and thermal properties of Cu-Ta films prepared by magnetron sputtering

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ABSTRACT

The microstructure, electrical resistivity and thermal conductivity of the sputtering deposited Cu-Ta films were investigated as a function of Ta content. The results showed that the amorphous phase formed between 20 at.% and 60 at.% Ta, and out of this range α-Cu(Ta) and β-Ta(Cu) solid solutions formed. Because the lattice distortion and β-Ta structure could significantly increase the probability of electron scattering, the electrical resistivity of the Cu-Ta films shows a 'N' type change with the increase of Ta content, and the inflection point appears at 50 at.% Ta and 60 at.% Ta respectively. As the thermal conductance is also dominated by electrons in metals films, an opposite variation tendency is found in the thermal conductivity of the Cu-Ta films. According to our knowledge, this is the first time to measure the thermal conductivity of Cu-Ta thin films.

1. Introduction

Cu-Ta alloys are typical immiscible alloys with formation heat of +3 kJ/mol, and there are no intermetallic compounds or intermediate phases in the binary Cu-Ta equilibrium phase diagram [1]. The properties of these immiscible alloys present a specific combination of the intrinsic physical properties of the elements, which can be flexibly and accurately controlled by composition design to suit the various requirements. Since the metal Ta has a high melting point and Cu has an excellent electrical conductivity, the effective combination of the two makes the Cu-Ta would be hoped to simultaneously use as a good thermal conductive and electrically conductive material. Much attention has been focused on the structure and mechanical properties of these alloys [2–4]. While the electrical and thermal behavior of the alloys have been studied in rather limited extend [5].

The phase structure of sputtered Cu-Ta films is related to the elemental composition. In general, as the Ta content increases, the fcc structure solid solution, amorphous phase and bcc or β-uranium structure solid solution are formed successively [2,6,7]. In alloys, the electrons are strongly scattered by solute atoms. The immediate consequence is a reduced ability of electrons to carry current and heat, and thus the lattice contribution will have a proportionally larger influence on the overall electrical conductivity and thermal conductivity [8]. Thermal properties of the films are as important as their mechanical and electrical properties in modern science and technology. However, there are very few quantitative date on thin film thermal properties as its measurement techniques is difficult [9]. As the structure of the Cu-Ta films changes with the composition, it is necessary to study the electron scattering behavior of the films systematically. Especially the effect of the structure on the thermal properties, according to our knowledge, the thermal performance of the Cu-Ta films has not been studied.

The present study prepares Cu–Ta films with different Ta content on Si wafer and Mo foil substrates by a co-sputtering process. The structures, electrical and thermal properties of the film are characterized as a functions of Ta content. The variation of electrical resistivity and thermal diffusivity reflects the changes in structure and composition of the films. A qualitative method for measuring the thermal diffusivity of a metal film is proposed.

2. Experimental details

The Cu-Ta films were deposited by dual-target magnetron sputtering (MIS800). The two magnetron were arranged in a confocal mode. Cu and Ta targets for sputtering were 99.99% and 99.95% pure, respectively. The Si (100) wafer and commercial available pure molybdenum foil (12 μm in thickness) were individually used as substrate. The Mo foil was boiled in 0.5 mol/L NaOH solution for 15 min, firstly. Si wafer and Mo foil substrate were ultrasonically cleaned using acetone and alcohol. Prior to film deposition, possible surface contamination on the substrate was remove by Ar^+

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sputter cleaning with 600 eV/50 mA for 15 min. During the deposition, the substrate was cooled down by water, which kept temperature of 22 ± 0.5 °C. The base pressure was less than 5×10^{-4} Pa and the working pressure was 1 Pa with Ar flow kept at 60 sccm. The composition of the film was regulated by adjusting the power ratio of the Cu target and the Ta target and then confirmed by energy-dispersive spectroscopy (EDS). In order to balance the stress, the Mo foil was coated with the same film on both sides to form a sandwich structure. The difference in composition between the two films confirmed by EDS is less than 1%.

The phase structures of the films deposited on Si substrate were analyzed by X-ray diffraction (XRD) measurement (Siemens D5000). Cross section analysis including thickness and morphology of the films on these two kinds of substrates were taken in scanning electron microscope (SEM, Hitachi S-4800). In combination with the thickness date, four-point probe measurements were used to determine the resistivity of the films deposited on Si substrate. Each sample was measured ten times at different locations. Thermal diffusivity of the composite films with sandwich structure and the Mo foil was measured using the laser-flash method (Netzsch LFA 467) in in-plane measurement mode at 25 °C. The composite films (Φ 25 mm) for thermal conductivity measurements were prepared by a tablet press.

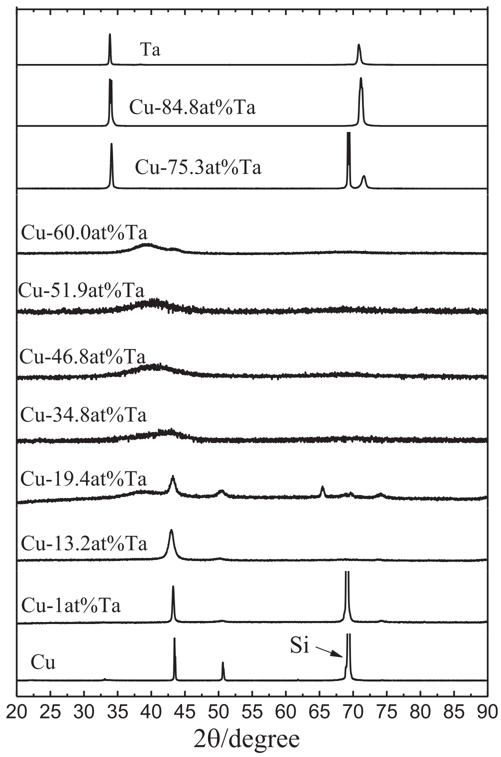

Fig. 1. XRD pattern of sputter deposited Cu-Ta films with different compositions.

3. Results and discussion

The XRD pattern of full range composition of Cu-Ta films are shown in Fig. 1. The crystal diffraction peaks and the broad amorphous peak shift towards smaller angles as the Ta content increases. The structures of the Cu-Ta films with the increase of Ta content are α-Cu(Ta) solid solution, amorphous and β-Ta(Cu) solid solution, successively. Amorphous composition is ranging from 20 at.% to 60 at.% Ta, as was observed in previous work [10]. As the XRD pattern shown, the phase is pure and no oxide diffraction peak is detected.

Fig. 2(a) and (c) show the surface and cross-sectional SEM images of Cu-13 at.% Ta, respectively. Regular grain distribution is clearly seen on the surface. A dimple-style structure is observed in the cross-sectional image, it may be that a few Ta particles act as diffusion barrier element to suppress the growth of columnar crystals. A

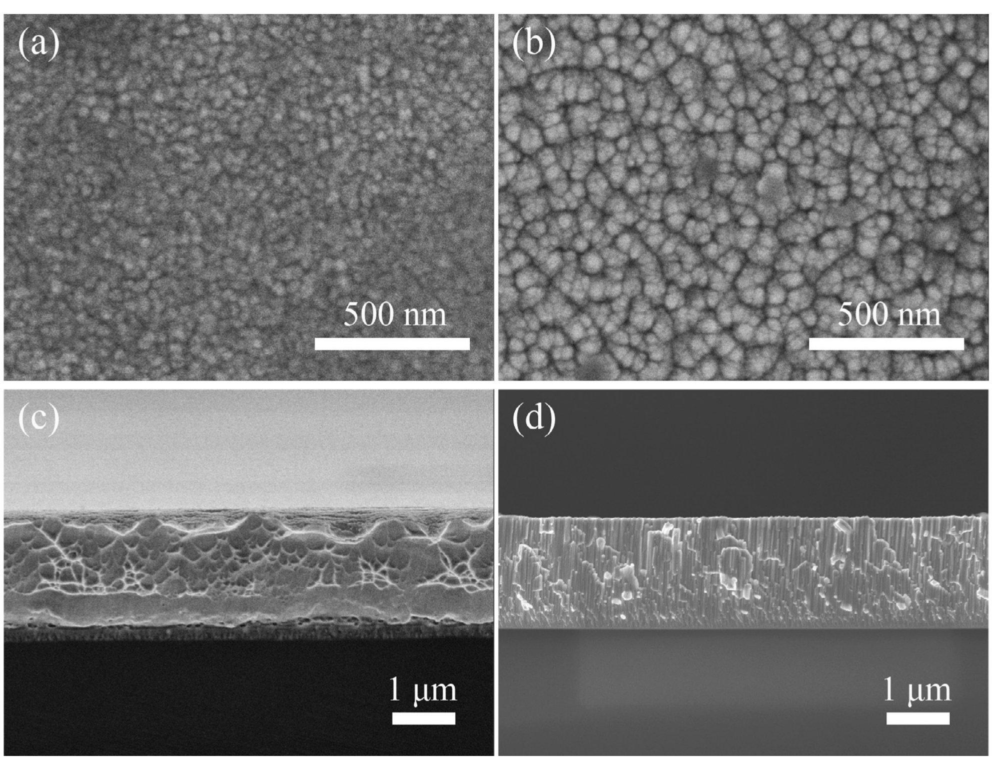

Fig. 2. Surface and cross sectional SEM images of Cu-13 at.% Ta (a, c) and Cu-81 at.% Ta (b, d) film on Si substrate.