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Effects of electric field annealing on the interface diffusion of Cu/Ta/Si stacks

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ABSTRACT

In the present paper, the effects of electric field annealing on interface diffusion of Cu/Ta/Si stacks were studied by means of XRD, XPS and TEM. The barrier property of Ta films was evaluated based on the diffusion of Cu atoms. It was found that the external electric field accelerates the diffusion of Cu atoms through Cu/Ta/Si interfaces during annealing. With the increment of annealing temperature, the effect of the electric field upon the atomic diffusion becomes more significant. The mechanism of accelerated interface diffusion is suggested and the failure of Ta barrier layer is discussed based on the mobility of vacancies and Cu atoms inside Cu/Ta/Si stacks caused by the electric field.

1. Introduction

One of the hot topics for metal interconnects is to insure the work stability in integrated circuits (ICs), as the feature size of ICs is shrinking continually [1]. It is well known that the work stability of Cu interconnects has an advantage over other metals for application in ICs, although the Cu diffusion is still to be solved [2]. At present, adding a thin diffusion barrier on Cu is thought to be an effective way to impede Cu diffusion into Si substrate [3–5]. Candidates for the barrier are certainly refractory metals and their nitrides with characteristically high melting points and chemical inertness [6–8], in which Ta based barriers have been generally used for Cu interconnects in industry [9–13].

Most investigations mainly focused on the influence of annealing temperature on the barrier property [14–20]. The work environment of the metal interconnect structure, however, is much more complicated in real application. Apart from temperature field, stress, electric and magnetic fields might also affect the barrier property. Wu et al. indicated that the development of grain growth and cube texture of rolled pure nickel was retarded by the external electric field (E) during annealing [21]. Cao et al. found that the grain growth of Cu was accelerated by the external electric field during annealing [22]. Zuo et al. reported that the electric field postpones the recovery and recrystallization progress of cold-rolled 3104 aluminum alloy sheets and the lattice distortion and grain growth of transitional carbides are affected by the magnetic field [23–25]. Both the electric and magnetic fields have been found to have a significant influence on the mobility of atoms, vacancies and dislocations in metals during annealing, such as Ni, Cu and Al [21–28]. However, the influence of external electric field on the barrier property during annealing has never been reported.

In this paper, we introduced electric field annealing into the investigation of the interface diffusion of Ta barriers in Cu interconnects. An accelerating behavior on Cu atomic diffusion by the external electric field was found and the corresponding mechanism was also discussed.

2. Experimental procedures

The nanocrystalline (NC) Ta and Cu films were deposited on (1 1 1) Si substrates by DC magnetron sputtering. After a cleaning by alcohol for 20 min in an ultrasonic bath, the substrates were immediately loaded into the sputtering system. First, NC Ta films of ~22 nm thickness were deposited on Si (1 1 1) substrate in pure argon gas using a 99.95% purity Ta target. The base and working pressure of the sputtering chamber was 2×10^{-4} Pa and 1.1 Pa respectively. The detailed deposition process of NC Ta films on Si substrates was described in our previous research, and Ta layer shows NC microstructure with α and β Ta mixed phases [3]. On the top of the NC Ta film, a Cu film of about 400 nm thickness was subsequently deposited under a DC power of 80 W to gain a Cu/Ta/Si stack. All targets were pre-sputtered before deposition to remove contaminants. To examine the work stability of the Cu/Ta/Si stack, thermal annealing at 450–650 °C for 30 min with and without electric field of 3 kV/cm was applied in a vacuum of 1×10^{-4} Pa. The electric field was perpendicular to the stacks. A schematic of the electrical arrangement was presented elsewhere [22].

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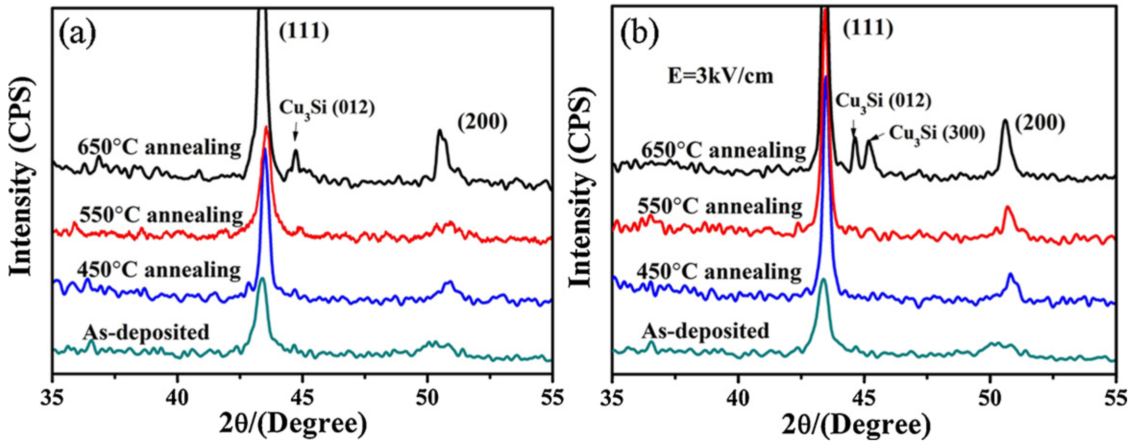

Fig. 1. XRD patterns of Cu/Ta/Si stacks including as-deposited and those annealed at different temperatures for 30 min without (a) and with (b) electric field.

The microstructure and thermal stability of the Cu/Ta/Si stacks were characterized by X-ray diffraction (XRD) (Rigaku, Ultima-III). The composition profiles of the stacks were examined by using X-ray photoelectron spectroscopy (XPS) (Thermofish, K-alpha). Transmission electron microscopy (TEM) (JEM-2100) was used to examine microstructure evolution of the interfaces of Cu/Ta/Si stacks.

3. Results and discussion

Fig. 1 shows the XRD spectra for the as-deposited Cu/Ta/Si stacks and those annealed at different temperatures with and without electric field. As can be seen from Fig. 1, the predominant reflection line for Cu (1 1 1) and those for Cu (2 0 0) at weak intensity are observed, which indicates that Cu film on the NC Ta film has preferential (1 1 1) crystal orientation. This is the prevalent characteristic of the Cu film prepared by sputtering methods [3]. The peaks become progressively sharper and stronger with the increased annealing temperature, which is attributed to the growth of Cu (1 1 1) grains induced by the annealing. The (1 1 1) texture is still dominant in the Cu film after annealing. Moreover, the electric field does not change the grain orientation in the Cu film. No peaks related to the silicide material were detected in both annealed cases at the 450 or 550 °C for 30 min. The onset of the inter-diffusion and

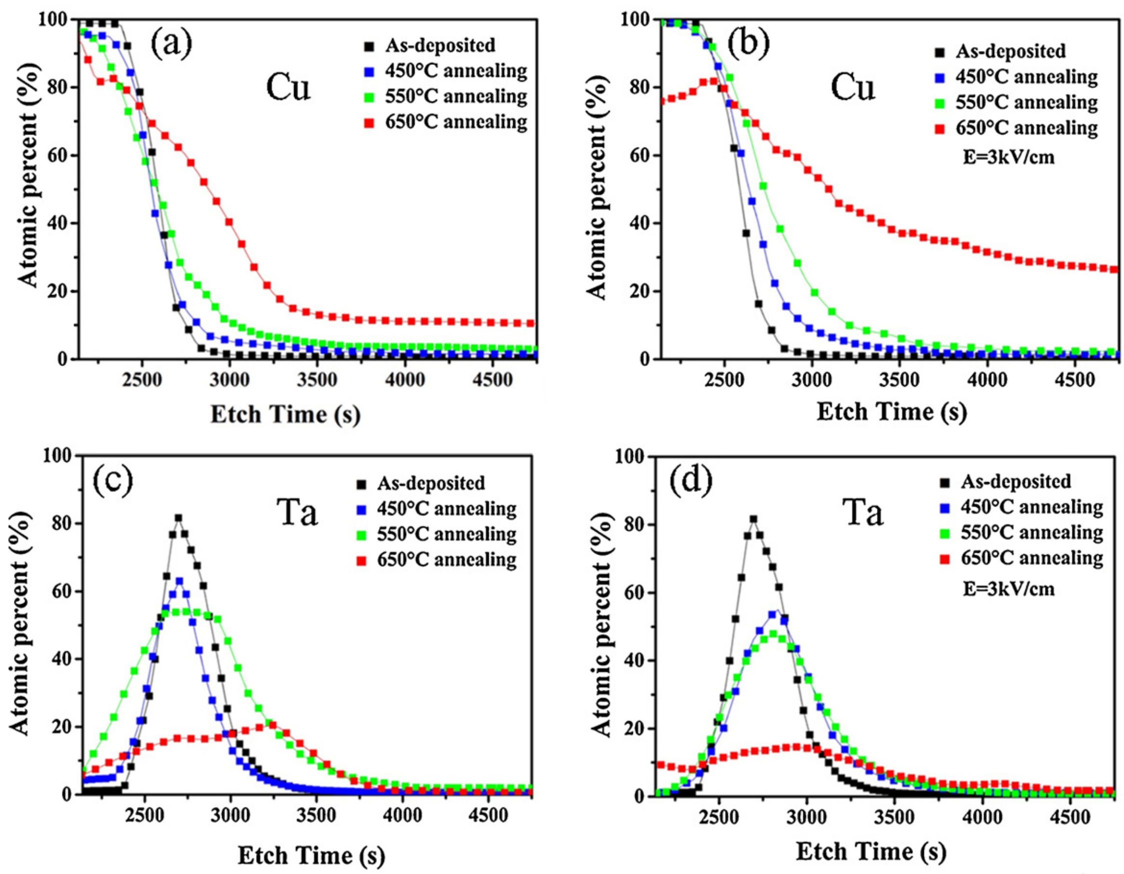

Fig. 2. XPS depth profiles of Cu and Ta in Cu/Ta/Si stacks of as-deposited and those annealed at different temperatures without (a and c) and with (b and d) electric field.