Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

ELSEVIER

Acta Materialia 54 (2006) 679–687

Acta MATERIALIA

www.actamat-journals.com

Anelastic behavior of copper thin films on silicon substrates: Damping associated with dislocations

Dae-han Choi *, William D. Nix

Department of Materials Science and Engineering, Stanford University, 416 Escondido Mall, Bldg, 550, Rm. 554Q, Stanford, CA 94305, United States

Received 20 January 2005; received in revised form 27 September 2005; accepted 5 October 2005
Available online 22 November 2005

Abstract

A dynamic measurement system has been developed to investigate damping in thin metal films. This system includes a vacuum chamber, in which a free-standing bi-layer cantilever sample is vibrated using an electrostatic force, and a laser interferometer to measure the displacement and velocity of the sample. With this equipment, internal friction as low as 10^{-5} in micrometer thick metal films in the temperature range 300–800 K can be measured. Using this system, the internal friction of Cu thin films was measured and an activation energy of 1.47 ± 0.05 eV was obtained from the internal friction peaks. Based on the dependence of the internal friction on the temperature, the frequency and the thickness of the film, we suggest that this activation energy points to a dragging mechanism of jogs accompanied by vacancy diffusion along the dislocation core. The proposed mechanism is modeled and compared with experimental results.

Keywords: Copper; Thin films; Anelasticity; Dislocation; Thermally activated processes

1. Introduction

As micro-electronic devices get smaller and faster, copper interconnects, with their higher conductivity, have replaced other metals such as aluminum to enhance the performance of the devices. Recently, therefore, many researchers have begun to investigate the properties of copper especially in the form of thin films. This research has revealed various microstructural behaviors of Cu that had not been observed in other interconnect materials, especially Al. Lee et al. [1] reported the grain growth and densification in electrodeposited copper films at room temperature. Electromigration experiments and microstructural studies also showed different activation energies and failure mechanisms [2]. The mechanical properties of Cu have also attracted much attention. The mechanical properties of Cu thin films have been studied mainly using quasi-static mechanical testing techniques, including tensile testing [3–6], nanoindentation [7,8], wafer curvature [9,10], microbridge deflection [11,12] and microbeam bending [13]. Thus, most information about the mechanical properties of Cu thin films obtained so far is static or quasi-static, based on the results from these testing techniques [14–16].

In the present paper, we focus on the dynamic response of Cu thin films and report the anelastic behavior of Cu thin films investigated with the dynamic testing system described in our previous work [17]. An internal friction peak is known to exist for bulk pure Cu at relatively high temperatures ($T > 0.5T_m$) [18,19]. In past investigations, the internal friction peaks for bulk Cu are observed in the temperature range of 500–700 K for both single- and polycrystalline samples, indicating that these peaks are not associated with grain boundaries. Roberts and Barrand [18] associated the damping in face-centered cubic FCC metals with the movement of jogs in the boundary but their argument was based primarily on a qualitative picture. Recently, Hagen et al. [20] studied the internal friction of Cu films on silicon substrates and observed peaks around 600 K. They argued that the dislocations anchored at the film/substrate interface and at the surface are responsible for the damping in Cu films. However, they did not offer

---

* Corresponding author. Tel.: +1 510 572 4207.
E-mail address: daehan.choi@gmail.com (D.-h. Choi).

1359-6454/$30.00 © 2005 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.actamat.2005.10.003

a detailed explanation on how the movement of these confined dislocations is related to a thermally activated process. In the present paper, these two ideas, the movement of jogs and confined dislocations, are combined to explain the observed anelastic behavior of Cu thin films.

2. Experimental

Free-standing cantilevers with three different natural frequencies were fabricated using well-established IC fabrication processes. The cantilevers consist of Cu films, a few microns thick, on 80 μm thick Si substrates, which exhibit low damping. Copper films with thicknesses of 1, 2 and 3 μm were deposited by sputtering to investigate the thickness dependence of the internal friction.

The internal friction of the Cu films was measured with a newly developed system. In this system, the bi-layer cantilever sample was placed in a vacuum chamber and vibrated with an electrostatic force at its resonant frequency. The free decay of the vibration was measured with a laser interferometer and the internal friction was calculated from the rate of free decay. Details of the sample fabrication and the measurement system were presented in our previous work [17].

3. Results

3.1. Temperature and frequency dependence of the internal friction

The internal friction of a bi-layer composite structure that consisted of a 2 μm Cu film on an 80 μm thick Si substrate was measured. For a film of thickness t_f on a substrate with thickness t_s, the internal friction of the film Q_f^{-1} can be calculated from the measured damping of the composite Q_c^{-1} and the substrate Q_s^{-1} using

$$Q_c^{-1} = Q_s^{-1} + \frac{3B_f t_f}{B_s t_s} Q_f^{-1}, \tag{1}$$

where B_f and B_s, respectively, represent the plane strain moduli of the film and the substrate [21]. The internal friction of Cu films for three different frequencies from room temperature to 750 K is shown in Fig. 1. Eq. (1) was used to determine the damping of the film Q_f^{-1} from the measured damping of the composite structure Q_c^{-1} using $B_f = 170$ GPa, $B_s = 171$ GPa, $t_f = 2$ μm and $t_s = 80$ μm [13]. The plot for each frequency in Fig. 1 is the average from three independent measurements with the same sample. Three independent measurements showed very similar plots indicating that the process is reversible and there is no permanent change in the sample. In addition, during each measurement, the damping of the sample was measured three times and three damping values were averaged at every temperature point. That is, nine different values were averaged to obtain a single data point in Fig. 1.

As can be seen in Fig. 1, the positions of peak damping are around 600 K. These damping peaks are found at higher temperatures than those found for Al films [17]. The peaks for different frequencies are also closer to each other than are those for Al films, suggesting a higher activation energy for the thermally activated atomic process controlling this anelastic behavior. We have to know the positions of peaks with high precision to calculate the activation energy for the process responsible for this anelastic behavior. However, the positions of peaks are difficult to determine accurately due to the large amount of background damping. Other research groups have also observed this relatively large background damping in internal friction experiments on thin films [20,22]. In order to make these positions clearer, the background damping has to be subtracted from the original data. Some researchers have argued that irrecoverable processes cause the background damping, but the exact mechanisms are still not known [22]. Even though the exact mechanisms have not been identified, it has been commonly accepted that the background damping takes the form of a quadratic equation. Additionally, we applied two more assumptions to determine the background damping included in the experimental data (Fig. 1). First, we assumed that the background damping is zero at 0 K since the defects in the material are frozen and not capable of responding to the external loads at this temperature. The second assumption is that the measured damping at both low (300–350 K) and high temperatures (750–800 K) is mostly background damping. A plot of the estimated background damping made using these assumptions is shown in Fig. 1. While positions of peak damping can be influenced a little by the choice of background damping from different assumptions, the effect of different background damping on the activation energy calculated from the peak damping is minimal as can be seen in Section 5.1.

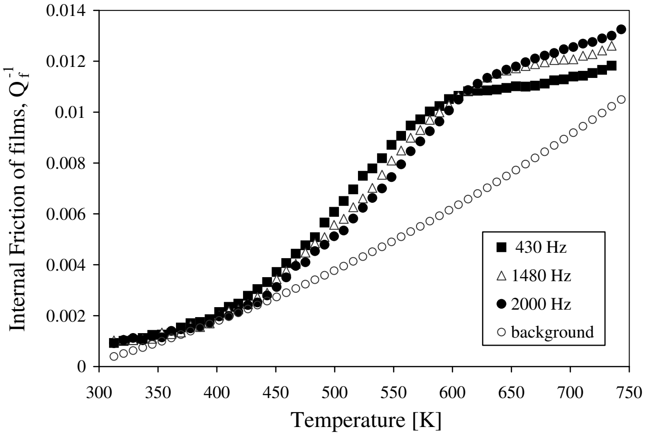

Fig. 1. Internal friction of 2 μm Cu films.

The internal friction of Cu films after subtracting the background damping is shown in Fig. 2(a). As can be observed in the figure, the plot resembles the theoretical form, the Debye function, and the positions of peak damping are obvious. As a matter of fact, the resultant plot is much broader than the theoretical Debye function. This