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Influence of a hot and humid environment on thermal transport across the interface between a Ag thin-film line and a substrate

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ABSTRACT

To evaluate the reliability of Ag thin-film lines for a wide range of applications in electronic devices, knowledge of the thermal transport across the interface between the line and the underlying substrate is of great importance. This is because such thermal transport significantly affects the temperature distribution in the line, the electrical performance of the line and the service life of the device the line is installed on. In this work, we examine the influence of a hot and humid environment on the thermal transport across the interface between a Ag thin-film line and a substrate. By performing a series of current-stressing experiments using the four-point probe method at atmospheric conditions (296 K and 30 RH%) on a Ag thin-film line for different durations of exposure to a hot and humid environment (323 K and 90 RH%), the electrical resistivity was found to increase with the exposure duration. Such an increase is believed to be the result of a decrease in the interfacial thermal conductance, which indicates less thermal transport from the line to the substrate. Moreover, by observing the surface morphology changes in the line and conducting a one-dimensional electro-thermal analysis, such variations can be attributed to the generation and growth of voids within the line, which hinder heat transfer from the line to the substrate through the interface.

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1. Introduction

With advantages over Cu in terms of electrical conductivity and over Al in terms of electromigration resistance, Ag thin-film lines have attracted a great deal of attention as an interconnect material for numerous potential applications, such as ultra-large-scale integration (ULSI) [1] and transparent conductive electrodes (TCEs) in electro-optical devices [2]. However, the increasing power requirements and decreasing device sizes stemming from the miniaturization and integration of these devices have led to rapid temperature increases generated by significant Joule heating. These rapid temperature increases are a critical factor in electrical failures because of the resulting increase in electrical resistivity and the acceleration of electromigration or corrosion. Therefore, effective thermal transport (or heat transfer, thermal dissipation) across the interface between a Ag thin-film line and a substrate has attracted significant attention as a key to highly reliable thermal designs. This is because the correspondingly high interfacial thermal conductance between the line and the substrate can significantly mitigate the temperature increase and elongate the service life of the corresponding device.

Generally, thermal transport across an interface is intimately related to the interface characteristics and the fundamental properties of the materials composing the interface itself [3–5], all of which are affected by the ambient environment. For example, it is known that Ag is prone to corrosion when exposed to moisture [6–8]. Additionally, it has been reported that Ag suffers agglomeration at high temperatures, restructuring the surface for energy minimization [9–11]. These facts indicate that the ambient environment will have a significant effect on the thermal transport across the interface between a Ag thin-film line and a substrate, which has not yet been systematically explored.

Therefore, this work aims to clarify the influence of a hot and humid environment on the thermal transport across the interface of a Ag thin-film line and a substrate. Here, a series of current-stressing experiments under atmospheric conditions (room temperature T_0 = 296 K and relativity humidity 30 RH%) were performed on a Ag thin-film line deposited on a Si substrate and exposed to a hot and humid environment (323 K and 90 RH%). The differences in the electrical resistivity and the interfacial thermal conductance of the line for different durations of exposure to this hot and humid environment were characterized. Moreover, using a combination of one-dimensional electro-thermal analysis on the

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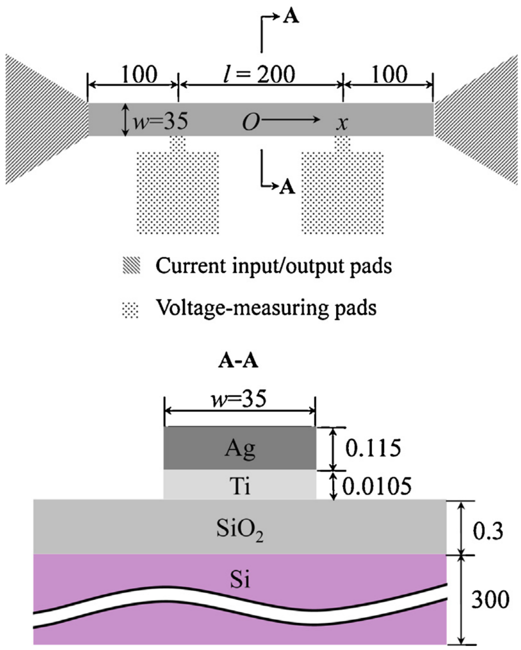

Fig. 1. Schematic structure of the Ag thin-film line deposited on a Si substrate: (a) top view and (b) cross-sectional view [unit: μm].

line and surface morphology observations, the underlying mechanism associated with these variations was clarified.

2. Experimental

2.1. Sample preparation

As schematically shown in Fig. 1, a Ag thin-film line deposited on a Si substrate was prepared using the following process. Initially, Ti thin film with thickness of 10.5 nm and Ag thin film with thickness of 115 nm were sequentially deposited on a thermally oxidized Si (1 0 0) wafer. The corresponding sputtering conditions and the film thickness are summarized in Table 1. Note that Ti was used to improve the adhesion between the Ag film and the Si substrate. Then, a conventional optical lithography process was applied to transfer the previously designed mask pattern onto the deposited Ag films, creating a Ag thin-film line for testing and two pairs of pads for current input/output and voltage measurements. The nominal length l and width w of the test line are 200 and 35 μm, respectively. Finally, a heat treatment was performed at 746 K for 30 min to improve the crystallization state in the Ag thin-film.

2.2. Current-stressing experiments

First, to investigate the thermal transport across the interface of the Ag thin-film line and the Si substrate, two groups of current-stressing experiments were performed under atmospheric conditions (296 K and 30 RH%) using the four-point probe method. The experimental conditions are summarized in Table 2. Note that the current was applied to the as-prepared samples, where the "±" indicates the direction of the current flow. For **Group I**, the Ag thin-film lines were stressed at different substrate temperatures T_s with different input currents I. Note that, to ensure that the effects of Joule heating were sufficiently small to be neglected, very small currents were employed here. Using the obtained voltage-current (V–I) relationship, the temperature-dependent electrical resistivity (i.e., electrical resistivity ρ_0 and temperature coefficient α at T_0) of the Ag thin-film line is evaluated. For **Group II**, the Ag thin-film lines were stressed at T_0 with different input currents I. Note that comparably large currents were employed to ensure that significant Joule heating took place, which differs from the conditions for Group I. Similarly, using the obtained V–I relationship, variations in the electrical resistivity as a function of the input current can be evaluated. Such results are used to predict the interfacial thermal conductance H between the line and the Si substrate, as introduced in Section 3.

Second, to investigate the influence of a hot and humid environment on the thermal transport across the interface between the line and the substrate, the Ag thin-films were stored in a hot and humid environment (323 K and 90 RH%) using a bench-top type temperature and humidity chamber (SH-222) before being removed and subjected to the two groups of current-stressing experiments conducted in atmospheric conditions, as described above. Using this method, the variation in the electrical resistivity and interfacial thermal conductance as functions of the different exposure periods t in the hot and humid environment are characterized.

Third, to explain the experimental results and explore the underlying mechanism, the changes in the surface morphologies of the Ag thin-film lines after exposure to different periods in the hot and humid environment were observed using field scanning electron microscopy (FE-SEM).

3. Theoretical prediction of the interfacial thermal conductance [12]

A previously proposed method [12], combining one-dimensional electro-thermal analysis of the line and experimental results on the variation of electrical resistivity with the input current, was employed to predict the interfacial thermal conductance H.

Table 1
Sputtering conditions used for sample preparation.

Sputtering conditions	Ti	Ag
Power [W]	150	150
Substrate temperature [K]	470	300
Sputtering period [s]	20	43
Film thickness [nm]	10.5	115

Table 2
Conditions for the current-stressing experiments.

Group	Conditions	Substrate temperature T_S (K)	Input current I ($\times10^{-3}$ A)	Unknown quantity for evaluation
I	(a)	296 ($T_s = T_0$)	±1, ±3, ±5	Electrical resistivity ρ_0 and temperature efficient α at room temperature
	(b)	373		
	(c)	449		
	(d)	526		
II	(e)	296 ($T_s = T_0$)	±100	Interfacial thermal conductance H
	(f)		±200	
	(g)		±300	
	(h)		±400	
	(i)		±500	

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