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Suitable passivation thickness on a metal line to prevent electromigration damage

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ABSTRACT

Electromigration (EM) is a serious problem for an Al line subjected to high-density electron flow. The present work reports a strategy for achieving a suitable passivation thickness on the line against EM damage. Experiments carried out in this work indicated that the threshold current density, a measure of EM resistance, increased with increasing passivation thickness and became saturated for thicknesses greater than 1700 nm. The saturation was shown to begin at the situation in which the level of the passivation top surface beside the Al line and that of the Al top surface are the same. A suitable passivation thickness for effectively increasing EM resistance was determined based on this finding.

1. Introduction

Electromigration (EM) failure has been a serious problem for electronic devices [1–4]. EM, which is a physical phenomenon of atomic diffusion with high-density electron flow, deteriorates a metal line. Short and open circuits are caused by hillocks and voids, which are formed by the accumulation and depletion of atoms, respectively. The deformation of a metal line resulting from EM has a negative effect on electronic reliability, and an effective way to prevent EM damage is required. Passivation is one of the countermeasures for EM damage because passivation slows the formation of hillocks and voids. Passivation has been generally utilized for insulating layers in electronic devices, and it is necessary to evaluate EM in consideration of passivation. Thick passivation restrains deformation of a metal line caused by accumulation of atoms, which allows higher atomic accumulation generating higher compressive pressure in a metal line. The influence of passivation on EM has been reported to generate back flow, which is due to a pressure gradient in the opposite direction to the atomic flux because of the electron wind force [5–7]. Therefore, consideration of passivation is extremely important for preventing EM.

The threshold length product $j_{th} \cdot l$ is one of the measures of EM resistance and is the product of the threshold current density j_{th}, below which no EM damage occurs, and the metal line length l, which is inversely proportional to j_{th} [8]. An increase in $j_{th} \cdot l$ increases the EM resistance. The product $j_{th} \cdot l$ is related to the passivation thickness, and the use of a suitable passivation thickness for increasing $j_{th} \cdot l$ is essential to prevent the initiation of EM damage in electronic devices. However, it is not easy to concisely determine a suitable passivation thickness for various sample structures.

This paper presents a way to increase $j_{th} \cdot l$ and a strategy for determining a suitable passivation thickness to effectively prevent EM damage, with results based on experiments.

2. Theory of threshold current density with passivation

An Al line is assumed to be constrained by coating with a passivation layer. Under the equilibrium conditions of two fluxes, which are due to the electron wind force and back flow, $j_{th} \cdot l$ is generated. The equation for $j_{th} \cdot l$ is expressed as follows [6,7,9]:

$$j_{th} \cdot l = \frac{\Omega \, \Delta\sigma_c}{|Z^*| e \, \rho}, \tag{1}$$

where Ω is the atomic volume, Z^* is the effective valence, which is negative in most metals, e is the electronic charge, ρ is the electrical resistivity, and $\Delta\sigma_c$ is the critical hydrostatic pressure difference, which is related to the passivation characteristics, thickness, and adhesion strength to the line. The pressure gradient in the direction of current flow caused by EM is $\Delta\sigma_c/l$ at the critical state of EM damage initiation.

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The effect of the passivation thickness on the lifetime of a metal line against EM has been reported [5,8,10–12]. However, the increase in EM lifetime and resistance by increasing passivation thickness will show saturation [11,13–15]. A possible explanation for the EM lifetime saturation with increasing passivation thickness was reported as delamination of passivation from the line [13]. This suggests the existence of a suitable passivation thickness. It is therefore essential to design a suitable passivation thickness, which corresponds to the beginning of saturation, to prevent time-consuming processes of thicker passivation.

In the present work, we aim to clarify the saturating nature of $j_{th} \cdot l$ with increasing passivation thickness by focusing on the sample structure. We examine the effect of passivation thickness on $j_{th} \cdot l$ and provide a new method for determining a suitable passivation thickness that can effectively prevent EM damage.

3. Experimental procedure

The effect of the passivation thickness on $j_{th} \cdot l$ was examined using the Blech structure [8], which is a conventional sample structure for investigating EM. The fabrication process for the testing sample structure is described in a previous work [16]. Using the prepared testing sample, $j_{th} \cdot l$ was measured utilizing the drift velocity, as previously reported [8]. We carried out the EM test under a fixed temperature of 573 K using a ceramic heater with five samples of the 500-nm-thick Al line, which were covered with 260-, 560-, 780-, 1700-, and 2800-nm-thick SiO_2 by plasma-enhanced chemical vapor deposition using tetraethyl orthosilicate (TEOS) as a liquid source (hereafter called TEOS passivation). The deposition conditions were chamber pressure of 53 Pa, radio-frequency power of 70 W, TEOS flow rate of 7 sccm, O_2 flow rate of 233 sccm, top electrode temperature of 473 K, and bottom electrode temperature of 623 K. The thicknesses of TEOS passivation were measured by cross-sectional images generated by focused ion beam.

4. Results and discussion

We demonstrate the EM tests for measuring $j_{th} \cdot l$ with various passivation thicknesses. The product $j_{th} \cdot l$ increased with passivation thickness and became saturated for passivation with thicknesses greater than 1700 nm, as shown in Fig. 1. To characterize the relationship between $j_{th} \cdot l$ and passivation, we introduce the new parameter h, which is defined as the difference between the level of the passivation top surface beside the Al line and the level of the Al top surface. We call h the level parameter. When the level of passivation beside the Al line exceeds the level of the Al top surface, h is defined as positive ($h > 0$). Fig. 1 shows the relationship between $j_{th} \cdot l$ and h. The product $j_{th} \cdot l$ increases with increasing h for $h < 0$, and it becomes saturated for $h \geq 0$. Fig. 2(b)–(d) shows examples of cross-sectional images of lines fractured by the accumulation of Al atoms for different h, which are captured at A-A, shown in Fig. 2(a), by FE-SEM. After applying a current density j greater than j_{th}, fractures were formed.

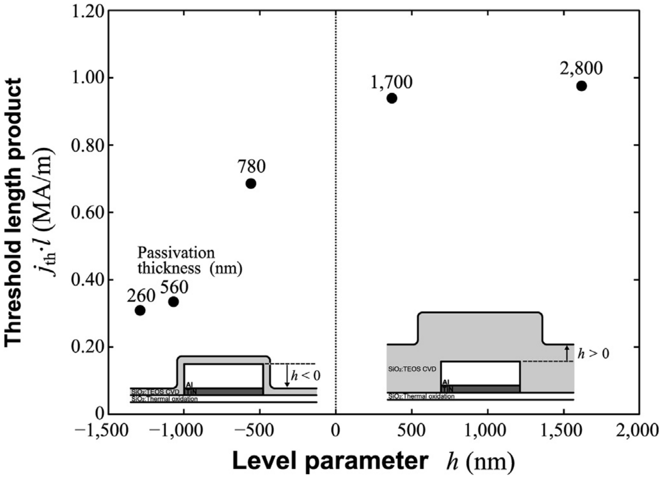

Fig. 1. Relationship between $j_{th} \cdot l$ and h at 573 K.

Fig. 3 shows the presumptive schematics of stress generation during passivation for fracture. Fracture appearances of Fig. 2(b) to (d) look similar to Fig. 3(a) to (c), respectively, where the value 370 nm of h for Fig. 2(c) seems to be well approximated by 0 nm for fracture. On the basis of the above experimental results, the zone near the corner of Al subjected to higher stresses, as shown in Fig. 2(e), would contribute to the strength of passivation against fracture. In contrast, a zone far from the corner of Al with lower stresses may not contribute to the strength of passivation.

Current stressing causes a pressure to the passivation by the accumulation of atoms, shown in Fig. 3. The increase and saturation of $j_{th} \cdot l$ with h is explained by the stress generation along the effective lengths aa' and bb' (see Fig. 3) with higher stresses in passivation.

Assume for simplicity that the TEOS passivation is an elastic-perfectly plastic material with the following basis: high temperature, which leads to softening of the TEOS passivation, is generated by substrate temperature and Joule heating under current stress [16]. On the TEOS passivation along the effective lengths aa' and bb', when the yielding condition is attained by accumulation of atoms at the anode end of the line, it is presumed that the deformation of the passivation significantly progresses perpendicularly to aa' and bb'. Then, it will lead to fracture of the TEOS passivation. A thin TEOS passivation makes it easy to reach the above critical state. In the case of $h < 0$, an increase in the passivation thickness decreases the stress on aa' and bb' by increasing the area composed of effective lengths aa' and bb'. In other words, EM resistance increases with increasing passivation thickness. In the case of $h \geq 0$, however, the following would be inferred from Fig. 1: because the areas composed of the effective length are subjected to higher stresses for fracture at $h = 0$, and would be similar at $h > 0$ [as shown in Fig. 3(b) and (c)], the saturation of $j_{th} \cdot l$ would begin at $h = 0$. As explained above, the use of a suitable passivation thickness corresponding to $h = 0$ can effectively prevent EM failure.

5. Conclusions

This paper proposed a strategy for determining the suitable passivation thickness to effectively increase the threshold length product $j_{th} \cdot l$ to prevent electromigration (EM). We examined the effect of passivation thickness on $j_{th} \cdot l$ and clarified the mechanism of saturation of $j_{th} \cdot l$ with increasing passivation thickness, where the level parameter h was introduced. The saturation of $j_{th} \cdot l$ begins at $h = 0$, where the level of the passivation top surface beside Al is equal to that of the top surface of the Al line. Deposition of passivation to the level of $h = 0$ is recommended for effectively increasing EM resistance with increasing $j_{th} \cdot l$.