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Electromigration behavior of advanced metallization on the structural effects for memory devices

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ABSTRACT

We investigated the kinetics of the electromigration (EM) phenomenon regarding not only metal line materials (Al, W, Cu) but also multiple structures of the Cu metal line under various electric conditions: direct current (DC), alternating current (AC) and pulsed DC. Under DC stressing, the W line had the longest EM failure lifetime, and the Al line had the weakest EM lifetime among Al, W and Cu materials due to the different diffusivity of the constitutional atoms. Lateral voids induced by joule heating were observed at the W contact of the Cu line fed with W, which decreased the lifetime compared with the Cu line fed with Cu. Although the mean time-to-failure was independent of the frequency of pulsed DC, the lifetime of the Cu line increased with the off-time of pulsed DC because the atomic migration was relaxed during the off-time period. This study provides guidelines for highly reliable memory devices with respect to multi-component structures under users' circumstances.

1. Introduction

The miniaturization of memory devices beyond the nanometer-scale has led to high current density in metal interconnects. High current density results in catastrophic failures of interconnects, which is a significant reliability issue. Open circuit failure or short circuit failure was induced by void generation and hillock formation in Al and Cu interconnects [1–4]. The origins of these failures are explained by electromigration (EM), which is the atomic displacement due to momentum transfer from carriers to metal atoms [5–7]. Recently, interconnects for integrated circuits (ICs) have consisted of various metals (e.g., W, Cu, and Al) to maintain high performance and low manufacturing costs. An Al metal line is easily and inexpensively patterned using conventional dry etching methods, W works as a stable contact material due to the high melting point, and Cu has a low resistivity [8]. For these reasons, memory devices have been developed as multiple structures of metal interconnects by choosing metal materials with various purposes for high performance. However, the EM reliability with respect to the structures of the interconnects remains underestimated, even though the EM behavior for each material has been known for decades. Because the reliability of memory devices is limited by the EM failure of the metal lines, it is crucial to investigate the kinetics of EM based on the structural and material effects to guarantee the reliability for future electronic devices. In addition, the EM behavior under pulsed electrical conditions is important because actual devices are operated using digital signals [9]. It is meaningful to evaluate the reliability of the Cu line with respect to the frequency and duty cycle of an electric pulse to accurately predict the actual EM lifetime [10].

In this work, we investigated the kinetics of the EM phenomenon considering not only the metal line materials (Al, W, and Cu) but also the multiple structures of Cu metal lines with different feeding materials, such as W and Cu, under direct current (DC) stressing. We also investigated the EM lifetime of Cu lines under AC and the EM dependency on the frequency and duty cycle under pulsed DC for the actual lifetime under users' circumstances.

2. Experimental

Twenty nanometer technology memory devices with a line-shaped structure were used for the study, and six types of sample structures were prepared, as depicted in Fig. 1: Al/W/Cu, Cu/Cu and Cu/W devices with upstream and downstream structures. To verify the effects of the metal materials and their connections with the contact material (W and Cu), the following were selected for component materials: Al/W/Cu, Cu/Cu and Cu/W. Each sample has 1 contact inlet and 3 contact outlets to prevent failure at the outlet. The metal line was longer than 100 μm, but the feeding length was fabricated with a sufficiently short length so it would not fail because of the Blech

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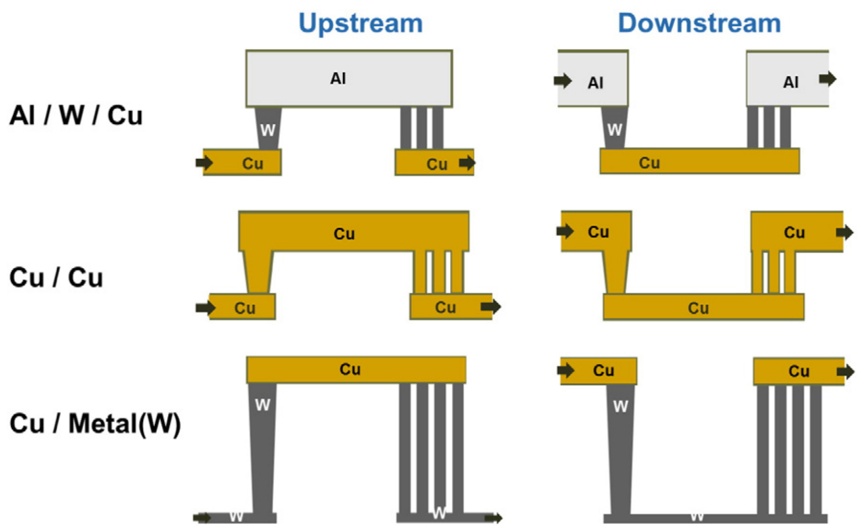

Fig. 1. Metal line samples for EM reliability tests: Al/W/Cu, Cu/Cu and Cu/W structures for the upstream and downstream.

effect [11].The changes of the electrical properties in the metal lines were evaluated on the package level. The criterion of failure was defined as a 10% change compared to the initial resistance. The range of temperature was 225–350 °C, and current density was imposed at 1–4 MA/cm^2. We applied AC and pulsed DC at a frequency of 10^{-4}–10^{-1} Hz and a duty cycle of 0.2–10 to evaluate the lifetime under AC and pulsed DC conditions compared to DC conditions.

3. Results and discussion

3.1. Electromigration on the structural effects

3.1.1. Al/W/Cu structure

The resistance change of Al/W/Cu in the upstream and the downstream structures was investigated, as shown in Fig. 2. The upstream structure showed significant increases of resistance under 3 MA/cm^2 at 250 °C, which originates from failure of the Al line in Fig. 2(a), whereas the downstream structure showed relatively gradual resistance increases of the Cu line, originating from the gradual failure of the Cu line, despite the higher temperature of 300 °C (>250 °C for upstream), as shown in Fig. 2(b). To clear the failures, focused ion beam (FIB) analyses were conducted. A large Al void on the W contact was found in Fig. 2(c), and a small void under the W contact was observed in Fig. 2(d). This phenomenon can be explained by the low melting temperature of the Al material, resulting in void generation and large expansion on the contact as a flux divergence site, as shown in Fig. 2(e). Under accelerated conditions, Al atoms can be easily activated, and atoms migrate by electron wind force. However, the failure of the Cu line at the downstream structure occurred with a relatively gradual resistance increase, and a void was generated under the W contact, which expanded but remained relatively smaller than that of the Al line, as shown in Fig. 2(f). This difference can be explained by the melting point. The higher melting point of Cu materials results in lower diffusivity, and Cu atoms migrate with difficulty. Despite the void generation, the diffusion barrier metal (Ta/TaN) for the Cu line acted as a conduction path on the sides and bottom of the Cu line because of the single damascene structure. The EM lifetime of the Cu line was longer than that of the Al line fed with the W contact.

3.1.2. Cu/Cu structure

The EM behavior of the Cu/Cu upstream and downstream structures was investigated at 300 °C and 3 MA/cm^2. For the upstream structure of the Cu line, no failure was observed for a long time, as shown in Fig. 3(a), whereas the downstream structure for the Cu line showed the typical gradual failure, as shown in Fig. 3(b). The Cu line at the upstream structure had a much longer lifetime compared to the downstream structure, even under the same temperature and current density. The upstream structure was more reliable than the downstream structure for EM reliability. As shown in Fig. 3(b), the typical gradual failure behavior at the Cu/Cu downstream structure originated from the void nucleation and gradual growth occurred with the conduction path of Ta/TaN. Fig. 3(c) showed that the Cu void was formed under the Cu contact.

Compared with the Al/W/Cu structure, the EM lifetime of the Cu line was different based on the contact material species; the EM lifetime of the Cu line fed with the W contact at the Al/W/Cu downstream structure in Fig. 2(b) was shorter than the lifetime of the Cu line fed with the Cu contact at the Cu/Cu downstream structure in Fig. 3(b). The resistance change of the Cu line at the Cu/Cu downstream structure showed a relatively gradual increase compared to the Cu line at the Al/W/Cu downstream structure, despite having the same dimensions and test conditions. This electrical difference can be explained by the void shape difference between the Cu fed with W contact and Cu fed with Cu contact in Fig. 2(d) and Fig. 3(c). For the Cu/Cu downstream structure, the void was generated under the edge of the contact and then expanded along the shortest path of electrons, indicating that the Cu line remained behind the void under the contact and acted as the conduction path with the Ta/TaN barrier metal. Therefore, the resistance gradually increased if the void elongated along the direction of electron flow. In Fig. 3(c), Cu was present in half of the contact bottom area, whereas the void was enlarged in half of the contact bottom (dash lines). As a result, the Cu line acted as a conduction path and caused a gradual increase of resistance. For the Al/W/Cu downstream structure, the Cu void shape under the W contact laterally expanded compared to the Cu void under the Cu contact in Fig. 2(d). Finally, the Cu line and W contact were burned out, and the resistance increased. Consequently, the interface of the upper Cu with a Ta/TaN barrier metal layer and under the Cu acts as a divergence site, but the interface of W via the WN barrier metal layer and under Cu acts as a divergence site and as a joule heating site, resulting in the lateral expansion of the voids and a relatively abrupt increase of the resistance compared to the Cu/Cu downstream structure.

3.1.3. Cu/W structure

We observed no failure of the W line at the Cu/W structure in Fig. 4(a), even though the downstream structure was weak regarding EM reliability, as indicated by the Cu/Cu structures. Among Al, Cu and W, W has the highest melting temperature and lowest diffusivity. It can be concluded that there was no EM failure for the W materials