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A physics-based electromigration reliability model for interconnects lifetime prediction

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Dear editor,

When the technology node scales down to 14 nm, the back-end-of-line (BEOL) in IC design faces the more serious challenges [1, 2]. The high-density integration induced by the technology innovation increases the number of interconnecting layers and reduces the metal pitch, making the placement and routing of BEOL more difficult. Meanwhile, due to the size effects, the maximum tolerable current density in narrow dimensions of metal lines can no longer meet the requirements of driving current density in interconnects. The high current density and rapidly increasing resistivity add a large power dissipation burden to interconnects, which accelerates the reliability degradation of metal lines. Currently, the reported work has shown the exploration of electromigration (EM) reliability in advanced technology nodes by using the empirical prediction equations [3] or the finite element methods (FEM) [4]. However, the conventional methods without the consideration of microscopic physical effects would overestimate the time-to-failure (TTF) of EM. Although the FEM-based simulation guarantees the relatively high accuracy of EM assessment, the simulated process would be time-consuming, which is not acceptable for the large-scale prediction of BEOL.

Therefore, we propose a compact model to predict the EM reliability of interconnects efficiently, as shown in Figure 1(a). The interconnects are consisted of the metal layer (ML) and surrounding barrier layers (BL). Due to the electron wind (e-wind) influence, the metal ions have the trend of migrating towards the e-wind direction, thus leaving the vacancies generated near the cathode region [5]. In our model, we define a void formation region (VFR) to calculate the vacancies accumulation in stage I. The resistance of Cu line is assumed as constant during this stage. The percentage of vacancies in VFR is increasing over time owing to the metal ions migration from VFR to ML. Once the percentage reaches the critical value of nucleation [6], the void formation is regarded to begin as shown in stage II. At this stage, the resistance changes of Cu lines (ΔR) are mainly related to the height of void vertical extension (h_1). After the full void forms across the whole Cu line, the void starts to grow laterally in stage III. The barrier resistance (e.g., R_1, R_2) is a major contributor to the changes of total resistance, which depends on the length of void growth (l_2). The detailed equations of resistance calculation are referred to Appendix A. Figure 1(b) shows the resistance-time (R-t) curve evaluated by the proposed model. Great agreements can be found between the experimental data [7] and modeling curves at different temperatures. The results reveal that the EM degradation experiences three stages. At first, the resistance of interconnecting remains almost constant. The vacancies continue generating due to the migration of metal ions mainly affected by e-wind. Then, the resistance begins to increase and quickly reaches an abrupt failure. This can be explained that full void formation cuts off the current paths in the metal layer, elevating the resistance to a higher value. Finally, the resistance tends to gradually increase because of the void lateral growth along the metal line.

The proposed model provides an effective tool for EM lifetime prediction by recording the failure time when the relative resistance rises by 20%. Taken 7 nm ground rules as an example, Figure 1(c) shows the lifetime prediction under the different current densities, in which some data points below $j = 10$ MA/cm^2 are not shown completely because of no resistance degradation at the limited time. The failure time is gradually shortened when the current density continuously increases. And the higher temperature would accelerate the degradation process. The reason can be explained that the high temperature increases the migration probability of metal ions thus promoting the void formation. The results show that the lifetime of interconnects is less than 10 h with 20 MA/cm^2 current density at 250°C. Due to the recovery effect [8], the growing void would suffer a negative driving force of lattice strain gradient, thus having a trend of volume reduction. The volume relaxation factor is about 90% [9]. The shrink of void can mitigate the EM degradation to some extent. When the operation current is turned off, this influence will become dominant. Figure 1(d) shows

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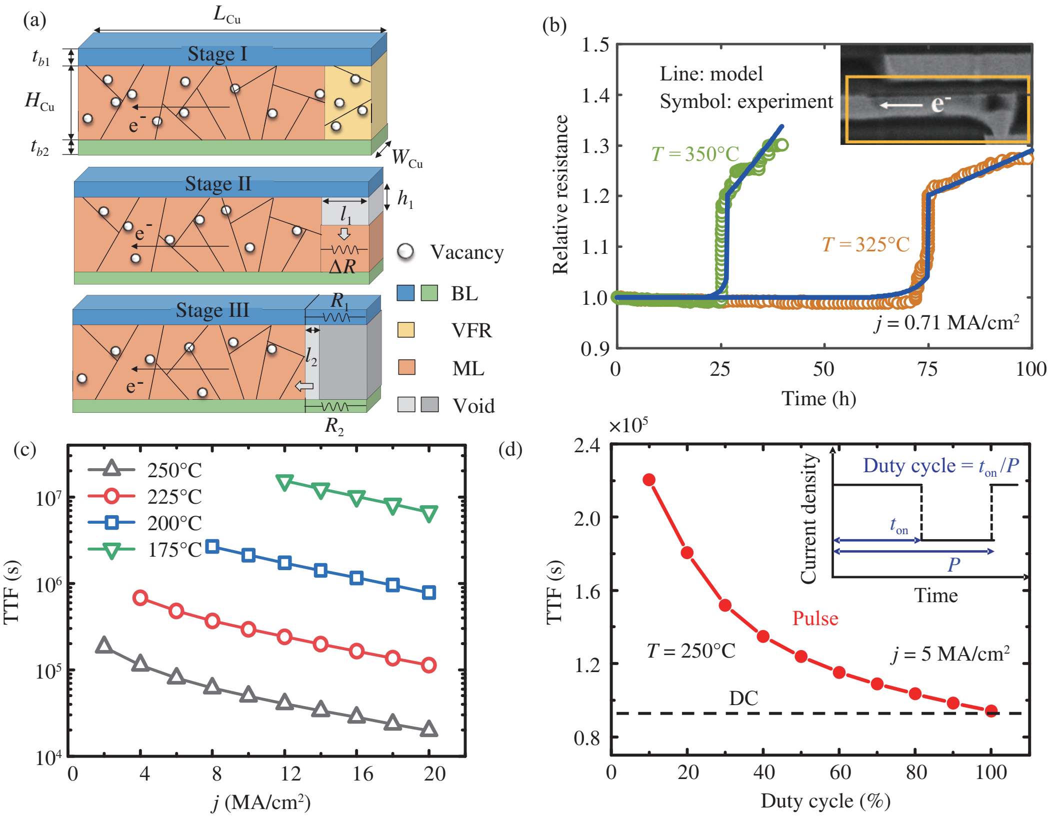

Figure 1 (Color online) (a) Physics-based EM reliability model of interconnects, which accounts for the process of resistance evolution; (b) modeling resistance evolution in comparison of experimental data [7]; (c) EM lifetime prediction with different operation current densities; (d) EM lifetime in pulse operation with different duty cycles.

the EM lifetime under the pulse operations by changing the duty cycles from 10% to 100%. The 100% duty cycle means the uninterrupted current input which is equivalent to DC operation. Considering the same current density and temperature, TTF increases with the reduced duty cycles.

Conclusion. In this study, we propose an EM compact model to predict the lifetime of interconnects. The microscopic metal ions migration is investigated to account for the resistance evolution. The predicted *R*-*t* curves indicate that the resistance degradation experiences the three stages: I- vacancies accumulation, II- void formation, III- full void growth, which corresponds to the experimental data. The lifetime of metal lines with large continuous current density at high temperature is much shorter than that under pulse operation. The proposed model provides a powerful tool to predict the EM failure accurately and efficiently in high-density multi-layer interconnects.

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Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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