A Physics-based Electromigration Reliability Model for Interconnects Lifetime Prediction

Supporting Information Appendix A

Model Description

In our model, we define a void formation region (VFR) to calculate the vacancies accumulation in Stage I. The resistance of Cu line (R_t) is assumed as constant during this stage, which can be expressed by Eq. (1), where ρ_{Cu} is the Cu resistivity, L_{Cu}, H_{Cu} and W_{Cu} stand for the length, height and width of Cu line respectively.

$$R_t = \frac{\rho_{Cu} \cdot L_{Cu}}{H_{Cu} \cdot W_{Cu}} \tag{1}$$

The increased percentage of vacancies in VFR (dPv) per unit time (dt) is attributed to the probability of metal ions migration from VFR to ML [1], as described in Eq. (2). Here f is the vibration frequency, k_B is the Boltzmann constant, T is the temperature, a is the lattice distance, l_1 is the initial length of void formation. It should be noted that the EM activation energy E_A can be affected by the modulated barrier of e-wind and stress (ΔE_{ew} & ΔE_{st}) [2]. The percentage of vacancies in ML (Pv_M) is updated simultaneously according to the migration of metal ions in ML, as shown in Eq. (3). Once the percentage of vacancies in VFR (Pv) reaches the critical percentage of nucleation [3], the void formation is regarded to begin.

$$dPv = dt \cdot f \cdot \exp\left(-\frac{E_A - \Delta E_{ew} + \Delta E_{st}}{k_B T}\right) \cdot Pv_M \cdot \frac{a}{l_1} \tag{2}$$

$$dPv_M = dt \cdot f \cdot \exp\left(-\frac{E_A - \Delta E_{ew} + \Delta E_{st}}{k_B T}\right) \cdot \left(1 - Pv_M\right) \cdot \frac{a}{\left(L_{Cu} - l_1\right)} \tag{3}$$

Stage II shows the process of void formation. The changes of R_t depend on the Cu resistance in VFR (ΔR), as calculated by Eq. (4), where R_{Cu} is the Cu resistance in ML, h_1 is the height of void that is determined by the new generated vacancies in VFR, as expressed in Eq. (5).

$$R_t = R_{Cu} + \Delta R \ , \ \Delta R = \frac{\rho_{Cu} \cdot l_1}{\left(H_{\mathrm{Cu}} - h_1\right) \cdot W_{Cu}} \tag{4}$$

$$dh_1 = dt \cdot f \cdot \exp\left(-\frac{E_A - \Delta E_{ew} + \Delta E_{st}}{k_B T}\right) \cdot \frac{a}{l_1} \cdot Pv_M \cdot \left(H_{Cu} - h_1\right) \tag{5}$$

After the full void forms across the whole Cu line, the void starts to grow laterally. During Stage III, the resistance in VFR (ΔR) in Eq. (6) is calculated by the four barrier resistances in parallel owing to the full void formation, where R_1 and R_2 is the resistance of top and bottom barrier layer. R_3 and R_4 is the two sides of barrier resistance.

$$R_t = R_{Cu} + \Delta R \ , \ \frac{1}{\Delta R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \tag{6}$$

$$R_1 = \frac{\rho_{b1} \cdot \left(l_1 + l_2\right)}{t_{b1} \cdot W_{Cu}} \ , \ R_2 = \frac{\rho_{b2} \cdot \left(l_1 + l_2\right)}{t_{b2} \cdot W_{Cu}} \ , \ R_3 = R_4 = \frac{\rho_{b2} \cdot \left(l_1 + l_2\right)}{t_{b2} \cdot H_{Cu}} \tag{7}$$

In Eq. (7), ρ_{b1} and ρ_{b2} mean the resistivity of barrier layer, t_{b1} and t_{b2} are the barrier thicknesses. Normally, the barrier material in the top layer is different from other sides [4]. The increased and decreased length of void (dl_2^+ & dl_2^-) are calculated in Eq. (8)-(9). Due to the recovery effect [5], the growing void would suffer a negative driving force of lattice strain gradient, thus having a trend of volume reduction.

$$dl_2^+ = dt \cdot f \cdot \exp\left(-\frac{E_A - \Delta E_{ew} + \Delta E_{st}}{k_B T}\right) \cdot Pv_M \cdot a \tag{8}$$

$$dl_2^- = dt \cdot f \cdot \exp\left(-\frac{E_A + \Delta E_{ew} - \Delta E_{st}}{kT}\right) \cdot \left(1 - Pv_M\right) \cdot a \tag{9}$$

References

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