Real-time Study of Sn Electromigration and Sn Whisker Growth by Synchrotron X-ray Nanoprobe

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Abstract

We conducted a real-time analysis on Sn electromigration behavior and Sn whisker growth in a Blech structure via synchrotron X-ray nanoprobe (beamline 23A, Taiwan Photon Source). Nano-X-ray fluorescence (nano-XRF) microscopy provided a dynamic visualization of the Sn depletion at the cathode and the Sn whisker/extrusion formation at the anode upon electron current stressing. A theoretical model based on the fundamental electromigration theory established by Blech and Herring [1] was proposed to characterize the dependence of Sn diffusion on the current stressing time and the Sn strip length. Finally, we concluded that the Sn electromigration was through the diffusion paths of Sn grain boundaries and lattice around room temperature. The good agreement between the electromigration model and the nano-XRF observation suggested that the X-ray nanoprobe technique enables to provide a nondestructive, in-situ characterization of the atomic diffusion in a thin-film structure.

Keywords - Synchrotron Radiation, nano-XRF, Electromigration, Sn Whiskers

Introduction

Electromigration is a mass transport phenomenon driven by an electric force and might result in material depletion (e.g., voids) at the cathode and accumulation (e.g., hillock/whisker) at the anode as a result of the induced atomic diffusion being along the electron flow. Electromigration-induced atomic flux (J_{EM}) is dominated by electron wind force and back stress and can be expressed as [1,2],

$$J_{\mathrm{EM}} = C\frac{D}{kT}\left(eZ^{*}\rho j - \frac{\Omega d\sigma}{dx}\right) \quad (1)$$

where C is the atomic concentration; D is the diffusivity; e is the electron charge (1.6×10^{-19} C); Z^* is the effective charge number of electromigration; ρ is the resistivity; j is the current density; k is the Boltzmann's constant (1.38×10^{-23} JK^{-1}); T is the temperature in Kelvin; Ω is the atomic volume; and $d\sigma/dx$ is the stress gradient between the cathode and the anode of the conducting line.

Electromigration of Sn might be a reliability risk to the electronic components because the Sn-based alloys (e.g., Sn-Ag-Cu alloys) and their coatings are widely in microelectronic packaging as micro joints or surface finish of fine Cu lines. When Sn electromigrated from cathode towards anode, a tensile and a compressive stress are therefore built up at the cathode and the anode end, respectively, leading to the Sn depletion at the cathode and the whisker/hillock growth out of the free surface from the weak points of the SnO_x film [2]. To advance fundamental understanding of the Sn depletion/whiskering mechanism induced by electric current, a real-time study of Sn electromigration via Blech structure [1] and synchrotron X-ray nanoprobe technique (beamline 23A, Taiwan Photon Source) was conducted to characterize the time-dependent Sn diffusion upon current stressing.

Experiments and Methodology

Fig. 1 illustrated the synchrotron X-ray nanoprobe setup and the Sn Blech structure utilized in this study. Nano-X-ray fluorescence (nano-XRF) microscopy through the synchrotron X-ray nanoprobe technique (12 KeV monochromatic X-ray with a focused spot size of 100 nm × 100 nm by a pair of Montel Kirkpatrick-Baez mirror) was employed to characterize the elemental distributions of the Blech structure as a function of current stressing time (t) and Sn strip length (L). Upon current stressing, the current density (j) over the Sn strips was 1.8×10^5 A/cm^2 and the surface temperature was measured as approximately 30 °C.

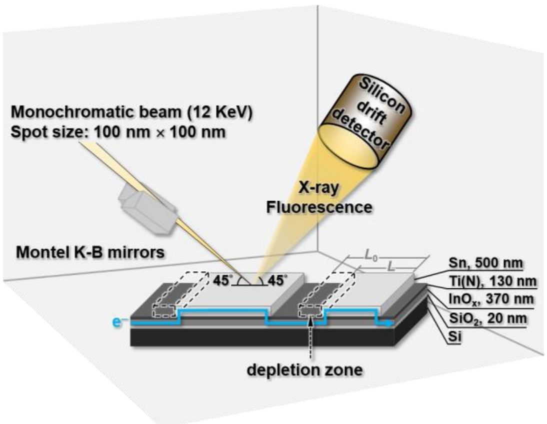

Fig. 1. Schematic illustration of the Sn Blech structure upon current stressing at the beamline 23A, TPS.

We conducted a mathematical analysis based on the electromigration theory to characterize the L–t relation [3],

$$L = \frac{-\left(\frac{D}{kT}eZ^{*}\rho jt - L_0\right) + \left[\left(\frac{D}{kT}eZ^{*}\rho jt - L_0\right)^{2} + 4\frac{D}{kT}\Delta\sigma\Omega t\right]^{0.5}}{2} \quad (2)$$

where D is taken to be 1.19×10^{-11} cm²/s in considering the Sn crystallographic orientation. T is 303 K, ρ is 12.6 μΩcm, $\Delta\sigma$ is 206.2 MPa [4], and Ω is 2.7×10^{-23} cm³.

Results and Discussion

Fig. 2 shows a series of XRF images of the Sn Blech structure, demonstrating Sn, Ti, and Si distributions upon current stressing. The depletion of Sn at the cathode and the formation of Sn whiskers/extrusions at the anode indicate that electromigration of Sn followed the electron direction. Meanwhile, the residual strip length (L) of Sn gradually decreased with increasing t, except the L_0 = 10–20 μm case, suggesting the counterbalance between electron wind force and back stress as L_0 = 10–20 μm, i.e., no Sn electromigration occurred at the shorter strips [2,3]. Additionally, no noticeable material damage can be found in the Ti(N) line (Fig. 2b–f), indicating that such a high current density is insufficient to induce the Ti electromigration.

To facilitate a quantitative evaluation of the electromigration dynamics in the Sn Blech structure, the L values as a function of t were measured and the results were plotted as the red dots in Fig. 3. The experimental L value of L_0 = 100 μm approximately decreased in a linear manner with increasing t (Fig. 3). The linear L–t dependence was ascribed to the electron wind force dominated the atomic flux $C\frac{D}{kT}eZ^*\rho j$ (Eq. 1) because the built-up back stress at longer Sn strips was still insufficient to overcome the electron wind force at the early stage of current stressing. A similar result can also be obtained for the L_0 = 75 μm case (inset, Fig. 3).

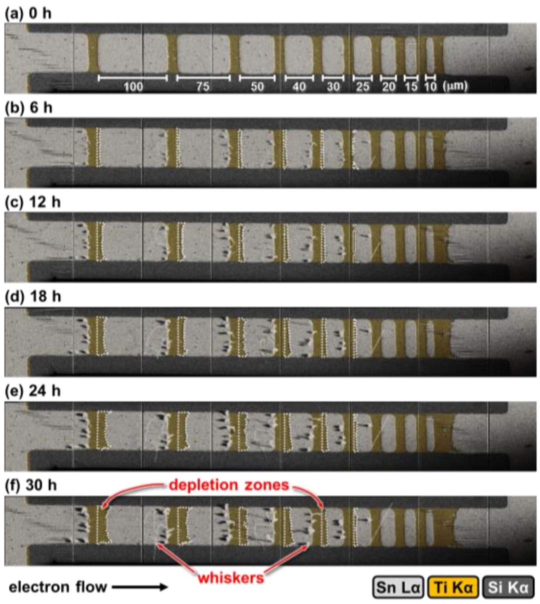

Fig. 2. Real-time nano-XRF mappings of Sn, Ti, and Si for the Sn Blech structure under current stressing of 1.8×10^5 A/cm² for t = (a) 0 h, (b) 6 h, (c) 12 h, (d) 18 h, (e) 24 h, and (f) 30 h.

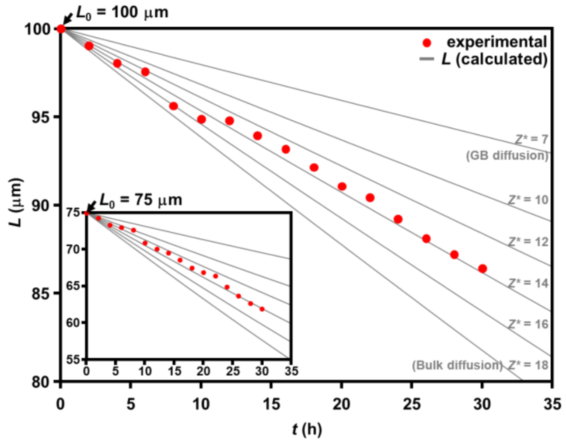

Fig. 3. Residual length of the Sn strip (L) as a function of t with respect to different Z^* values for L_0 = 100 μm. (Insert: L_0 = 75 μm)

The calculated L values of L_0 = 100 μm with Z^*= 7–18 were acquired from Eq. (2) and plotted as gray lines (Fig. 3), where Z^*_{GB} (7) and Z^*_{B} (18) represent the Sn diffusion via grain boundaries and lattice, respectively [5,6]. The experimental L values of L_0 = 75 μm and 100 μm fluctuated between Z^*= 12 and 16, suggesting that both bulk diffusion and grain boundary diffusion dominate the Sn electromigration around the room temperature (30 ℃). The results were quite reasonable because 30 ℃ reaches 0.6 homologous temperature (T_H) of pure Sn. The good agreement between the electromigration model (Eq. 2 and Fig. 3) and the nano-XRF observation (Fig. 2) suggested that the X-ray nanoprobe technique enables to provide a nondestructive, in-situ characterization of the atomic diffusion in a thin-film structure.

Acknowledgments

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References

[1] I. A. Blech, *Acta Mater.*, vol. 46, pp. 3717–3723, 1998.
[2] K. N. Tu, *J. Appl. Phys.*, vol. 94, pp. 5451–5473, 2003.
[3] C. E. Ho, W. Z. Hsieh, C. H. Yang, and P. T. Lee, *Appl. Surf. Sci.*, vol. 388, pp. 339–344, 2016.
[4] F. Yang, J. C. M. Li, Lead-Free Electronic Solders, Springer, 2006.
[5] A. Khosla and H. B. Huntington, *J. Phys. Chem. Solids*, vol. 36, pp. 395–399, 1975.
[6] C. Y. Liu, C. Chen, and K. N. Tu, *J. Appl. Phys.*, vol. 88, pp. 5703–5709, 2000.