AIP | Applied Physics Letters

Critical length of electromigration for eutectic SnPb solder stripe

C. C. Wei and Chih Chen

Citation: Applied Physics Letters **88**, 182105 (2006); doi: 10.1063/1.2200158
View online: http://dx.doi.org/10.1063/1.2200158
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/88/18?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

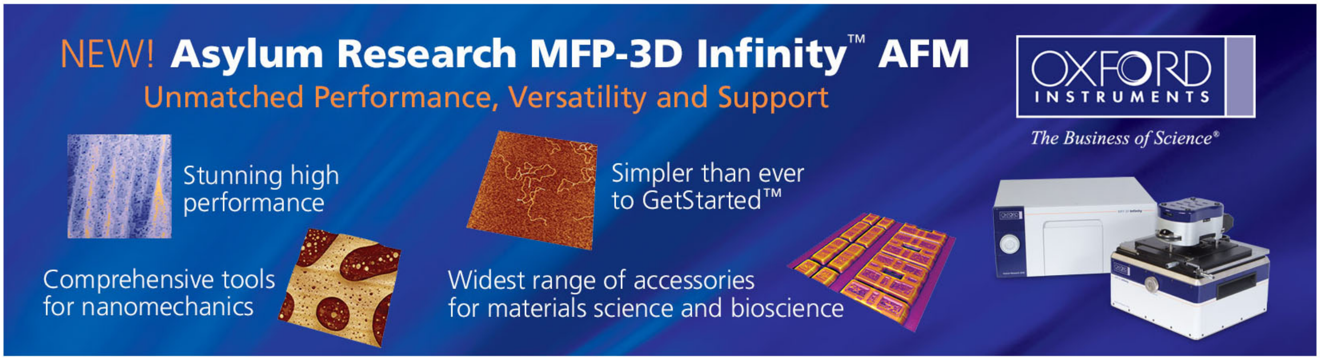
Relationship between edge drift and atomic migration during electromigration of eutectic SnPb lines
J. Appl. Phys. **100**, 033715 (2006); 10.1063/1.2210262

Electromigration and critical product in eutectic SnPb solder lines at 100 ° C
J. Appl. Phys. **100**, 024909 (2006); 10.1063/1.2216487

Redistribution of Pb-rich phase during electromigration in eutectic SnPb solder stripes
J. Appl. Phys. **99**, 054502 (2006); 10.1063/1.2178392

Threshold current density of electromigration in eutectic SnPb solder
Appl. Phys. Lett. **86**, 203504 (2005); 10.1063/1.1929870

Microstructure-electromigration correlation in a thin stripe of eutectic SnPb solder stressed between Cu electrodes
Appl. Phys. Lett. **75**, 58 (1999); 10.1063/1.124276


NEW! Asylum Research MFP-3D Infinity™ AFM
Unmatched Performance, Versatility and Support
Stunning high performance
Simpler than ever to GetStarted™
Comprehensive tools for nanomechanics
Widest range of accessories for materials science and bioscience
OXFORD INSTRUMENTS
The Business of Science®

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 140.113.38.11 On: Thu, 01 May 2014 01:59:54

APPLIED PHYSICS LETTERS **88**, 182105 (2006)

Critical length of electromigration for eutectic SnPb solder stripe

C. C. Wei and Chih Chen[a)]
Department of Material Science and Engineering, National Chiao Tung University, Hsin-chu, 30050 Taiwan, Republic of China

(Received 25 January 2006; accepted 15 March 2006; published online 4 May 2006)

The critical length of eutectic SnPb solder was investigated using solder stripes. By employing focus ion beam, solder stripes of various lengths, including 5, 10, 15, 20, 30, 100, and 200 μm, can be fabricated. Length-dependent electromigration behavior was observed, which implies that there may be back stress under stressing. The critical length was determined to be between 10 and 15 μm under stressing by 2×10^4 A/cm^2 at 100 °C, and the corresponding critical product was between 20 and 30 A/cm. Both values show good agreement with their theoretical values. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2200158]

With the portable devices becoming smaller and more compact in size, flip-chip technology has been adopted for fine-pitch packaging in microelectronics industry.[1] Area array of tiny solder joints can be fabricated on Si chips to achieve high-density packaging. In addition, as the required performance continues to increase, the input/output (I/O) pin count of flip-chip products has dramatically increased and the current that each bump needs to carry continues to increase, resulting in higher current density flowing in each solder bump. Therefore, electromigration (EM) has become an important reliability issue in solder joints.[2–4]

A lot of research has been done on electromigration of solder joints. However, only a few studies have been focused on the measurement of fundamental electromigration parameters of solder. Liu *et al.* found that the dominant diffusion species was Sn atoms in a thin SnPb stripe when stressed at room temperature.[5] Huynh *et al.* conducted another electromigration study at 150 °C using V-groove samples, and found that Pb atoms were the dominant diffusion species.[6] Yeh *et al.* used Blech structure to measure the threshold current density.[7] However, one of the fundamental parameters of electromigration, the critical length, has not been measured experimentally. The critical length represents the stripe length below which there was no electromigration damage due to balanced back stress.[8] The critical length for the Al and Cu lines has been investigated, from which an very important parameter, critical product, can be obtained.[8,9] The critical length of solder has not been measured because it is very difficult to prepare short solder stripes. In this letter, we report a technique that is capable of fabricating solder stripes with various lengths down to a few microns. Therefore, the critical length for solder can be obtained experimentally.

In general, the mass transport by electromigration in Blech specimens is governed by the following equation:[8,10]

$$J = \frac{CD}{kT} Z^* eE - \frac{CD}{kT}\frac{d\sigma\Omega}{dx}, \tag{1}$$

where J is the net electromigration flux, C is the atomic concentration per unit volume, D is the diffusivity, Z^* is the effective charge number, E is the electric field, k is Boltzmann's constant, T is the absolute temperature, σ is the hydrostatic stress in the metal, and Ω is the atomic volume. The first term on the right-hand side of the equation represents the flux due to electromigration, whereas the second term stands for the opposite flux due to back stress.[10] Under the same current density, the shorter the stripe is, the higher the back stress will be. Back stress increases with decreasing stripe length due to higher stress gradient. At the critical length, the stress balances with the wind force, and thus there is no net electromigration flux. If we assume that $-d\sigma/dx$ is equal to σ_c/L_c, the critical length can thus be expressed as

$$L_c = \frac{\sigma_c\Omega}{Z^* eE} = \frac{\sigma_c\Omega}{Z^* ej\rho}, \tag{2}$$

where σ_c is the stress at the critical length, L_c is the critical length, j is the applied current density, and ρ is the resistivity of the stripe.

To investigate the critical length of solder, short Blech stripes down to a few micrometers need to be fabricated. We have reported a technique for fabricating solder Blech stripes of 370 μm long in a Si trench.[7] Nevertheless, it is quite challenging to fabricate short solder stripes because it is very difficult to reflow the solder on underbump metallization (UBM) of less than 20 μm long. In addition, the thickness of the solder stripe was not uniform at both ends, since the two ends were thinner due to reflow and polishing process. To overcome these problems, focus ion beam (FIB) was employed to fabricate short stripes from the 370-μm-long solder stripe. Figure 1(a) shows the SnPb stripe of 370 μm long fabricated using our previous approach. The stripe was 80 μm wide and 2.1 μm thick. FIB was used to etch away part of the stripe, and desired lengths of solder stripes can thus be fabricated on a Blech specimen. Figure 1(b) shows the stripes with abrupt edges fabricated by the above technique. The FIB etched away three solder slices of 80×10 μm^2 at the desired positions. Various lengths, including 10, 30, 100, and 200 μm, can be fabricated on a Blech specimen. Figure 1(c) shows the tilt-view scanning electron microscopy (SEM) image for one of the surfaces after the FIB etching. The solder layer was almost etched away and it became discontinuous. The intermetallic compounds (IMCs) below the solder were also etched slightly, but it was still continuous. They might not migrate during the electromigration test, because Cu_6Sn_5 and Cu_3Sn IMCs have higher melting point and higher elastic modulus. They were expected to

---

[a)] Author to whom correspondence should be addressed; electronic mail: chih@cc.nctu.edu.tw

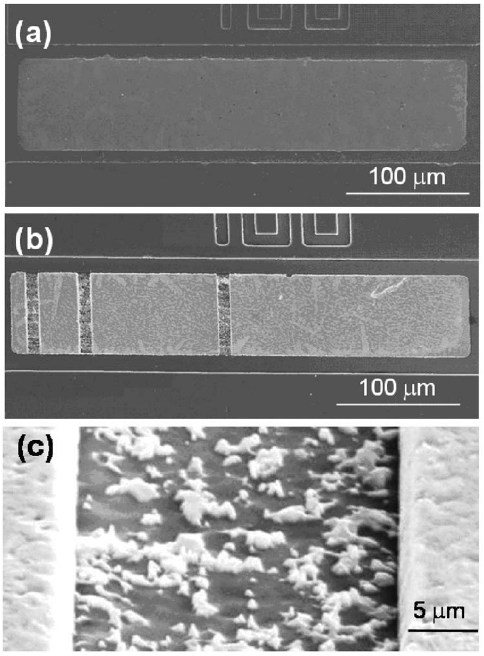


FIG. 1. (a) Plan-view SEM image for the fabricated solder Blech specimen of 370 μm long. (b) Plan-view SEM image for a solder Blech specimen after FIB etching. Solder stripes of 30, 100, and 200 μm long were fabricated. (c) Tilt-view SEM image showing the surface after FIB etching. Solder stripe became discontinued after etching.

have better electromigration resistance. The etching depth was controlled so that the Ti film remained intact, and thus it was able to carry the stressing current. Since the remaining solder/IMC on the etched surface became isolated, and their length might be shorter than the critical length of solder and IMC, they did not migrate during current stressing, thus affecting the electromigration behavior of the neighboring solder stripes. The sample was annealed at 150 °C for 5 h prior to electromigration testing to remove the damage in the solder caused by FIB etching.

Figure 2 shows the cross-sectional schematic for the solder stripes in Fig. 1(b). The IMC was about 0.8 μm thick, and the SnPb solder was about 1.3 μm thick. There was a 400 nm Cu metallization layer on a 120 nm Ti film before the reflow process, and it was almost consumed after the reflow process. Thus, there was almost no additional IMC formation during electromigration testing. Because the solder was thinner on both ends of the solder stripe in Fig. 1(a), the electromigration behavior for the solder stripe on the far left was not considered. During electromigration test, a constant current was applied through the pads on the two ends. There was around 80% of the applied current drifting in the solder strip, 19% in the IMC layer, and only 1% in the Ti layer.

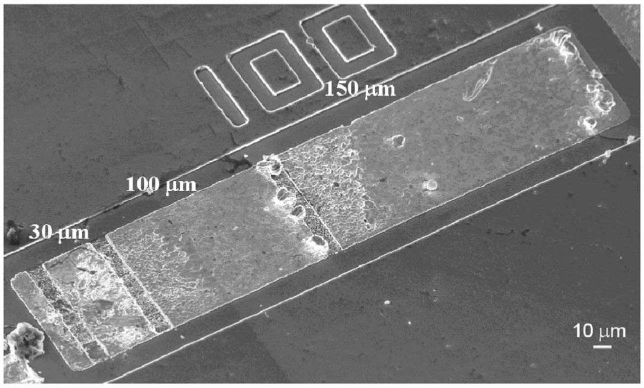


FIG. 3. Tilt-view SEM image showing the solder stripes in Fig. 1(b) after current stressing of 5×10^4 A/cm^2 at 100 °C for 104 h. Depletion occurred for all solder stripes, and it was larger for longer solder stripes.

Critical length of the solder stripe could be determined using these short strips. Figure 3(a) shows the same specimen in Fig. 1(b) after stressing by the current density of 5×10^4 A/cm^2 at 100 °C for 104 h. It is found that electromigration occurred in the three solder stripes of 30, 100, and 150 μm long. In addition, the longer the stripe is, the higher the electromigration rate will be. Length-dependent electromigration behavior was also observed on the solder stripes, which means that there may be back stress in the solder stripe under stressing. The critical length is below 30 μm from these results. To further explore the critical length, shorter solder stripes of 5, 10, 15, 20, and 30 μm long were fabricated, as shown in Fig. 4(a). Lower current density of 2×10^4 A/cm^2 was used in order to determine the critical length more precisely. After the stressing condition at 100 °C for 490 h, electromigration occurred in the stripes longer than 15 μm as indicated by the arrows in Fig. 4(b), yet no depletion was observed in those of 5 and 10 μm long, as shown in the figure. Therefore, the critical length for eutectic SnPb solder was determined to range between 10 and 15 μm. The corresponding critical product was between 20 and 30 A/cm.

To examine whether the measured critical length is reasonable, the theoretical value in Eq. (2) was estimated. We take the critical compressive stress in the anode end of the SnPb solder stripe to be the yield strength of solder, which is 27.2 MPa. Wang *et al.* reported that the stress gradient is linear in an Al stripe of 200 μm long,[11] therefore, it is assumed that the gradient in the solder stripe behaves linearly. If we assume that the tensile stress in the cathode end is also 27.2 MPa, the stress difference between the anode side and cathode side will be 54.4 MPa. In addition, Z^*, Ω, and ρ are taken to be 30, 2.78×10^{-23} cm^3, and 14.5×10^{-6} Ω cm, respectively. By substituting all the parameters in Eq. (2), the critical length is estimated to be 11 μm under the current density of 2×10^4 A/cm^2, which is quite close to our experi-

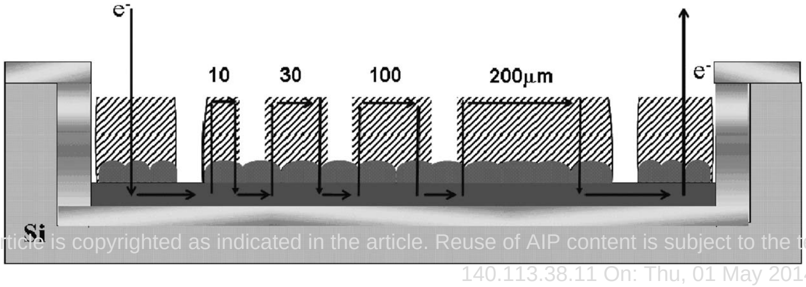


FIG. 2. Cross-sectional schematic of the solder stripe inside a Si trench. The solder layer and the IMC layer were about 1.3 and 0.8 μm thick, respectively.

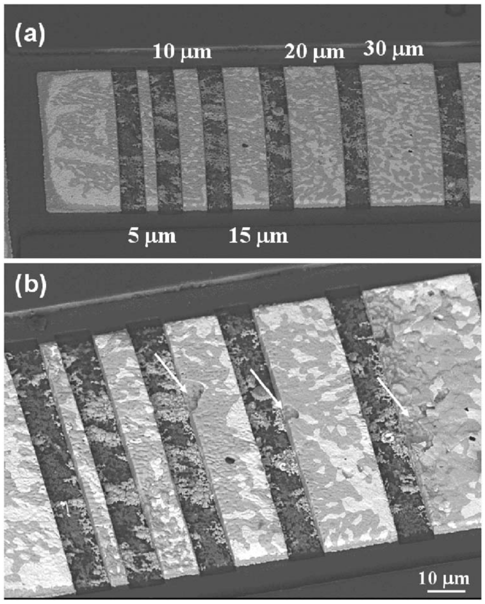


FIG. 4. (a) Back-scattered SEM image showing another solder Blech specimen with stripes of 5, 10, 15, 20, and 30 μm long before current stressing. (b) The same specimen in (a) after current stressing of 2×10^4 A/cm^2 at 100 °C for 490 h. No depletion was found for the 5 and 10 μm stripes.

mental value. The corresponding value of critical product is 22 A/cm.

It is estimated that the current density required to cause failure in a solder joint is about two orders of magnitude less than that needed for an Al or Cu line to fail.[3] Electromigration in a flip-chip solder joint occurs at lower current density because of the high lattice diffusivity in the solder alloys, together with higher resistivity, lower Young's modulus, and higher effective charge number of the chemical elements in solder alloys than those of Al or Cu. The critical product is 1260 A/cm for a 115 μm Al stripe at 350 °C,[8] whereas it is 3700 A/cm at 340–400 °C for dual-damascene Cu/oxide interconnects.[9] These values are about 50–150 times larger than those obtained in our experiment. Therefore, the critical product we measured is quite reasonable.

Significant phase redistribution was observed after current stressing for stripes longer than 15 μm, as shown in Fig. 4. The Pb-rich phase migrated toward the anode end, and thus Pb atoms were found to be the dominate diffusion species at 100 °C. This phase redistribution may have effect on the back stress. In addition, after stressing for a long time, the Pb-rich phase accumulated on the anode end, leaving the Sn-rich phase on the cathode end. This redistribution also affects the yield stresses on the cathode and the anode ends. Further study is needed to address these issues.

In conclusion, eutectic SnPb solder stripes of various lengths have been fabricated using FIB. It is found that no electromigration damage occurred for the 5 and 10 μm stripes under stressing by the current density of 2×10^4 A/cm^2 at 100 °C for 490 h, whereas length-dependent electromigration behavior was observed for longer stripes. The critical length was between 10 and 15 μm, which is quite close to the theoretical value of 11 μm. The corresponding critical product was between 20 and 30 A/cm, which is approximately two orders of magnitude smaller than that of the dual-damascene Cu/oxide interconnects.

The authors would like to thank the National Science Council of the Republic of China for financial support through Grant No. 93-2216-E-009-030.

[1] J. H. Lau, *Flip Chip Technology* (McGraw-Hill, New York, 1995), p. 123.
[2] *International Technology Roadmap for Semiconductors* (Semiconductor Industry Association, San Jose, CA, 2003), Assembly and Packaging Section, pp. 4–9.
[3] K. N. Tu, J. Appl. Phys. **94**, 5451 (2003).
[4] C. Y. Liu, C. Chen, C. N. Liao, and K. N. Tu, Appl. Phys. Lett. **75**, 58 (1999).
[5] C. Y. Liu, Chih Chen, and K. N. Tu, J. Appl. Phys. **88**, 5703 (2000).
[6] Q. T. Huynh, C. Y. Liu, Chih Chen, and K. N. Tu, J. Appl. Phys. **89**, 4332 (2001).
[7] Y. T. Yeh, C. K. Chou, Y. C. Hsu, Chih Chen, and K. N. Tu, Appl. Phys. Lett. **86**, 203504 (2005).
[8] I. A. Blech, J. Appl. Phys. **47**, 1203 (1976).
[9] E. T. Ogawa, A. J. Bierwag, K. D. Lee, H. Matsuhashi, P. R. Justison, A. N. Ramamurthi, and P. S. Ho, Appl. Phys. Lett. **78**, 2652 (2001).
[10] I. A. Blech, Acta Mater. **46**, 3717 (1998).
[11] P. C. Wang, G. S. Cargill, I. C. Noyan, and C. K. Hu, Appl. Phys. Lett. **72**, 1296 (1998).