Electromigration Studies of Cu/Carbon Nanotube Composite Interconnects Using Blech Structure

Yang Chai, *Student Member, IEEE*, Philip C. H. Chan, *Fellow, IEEE*, Yunyi Fu, Y. C. Chuang, and C. Y. Liu

***Abstract*—The electromigration (EM) properties of pure Cu and Cu/carbon nanotube (CNT) composites were studied using the Blech test structure. Pure Cu and Cu/CNT composite segments were subjected to a current density of 1.2×10^6 A/cm^2. The average void growth rate of Cu/CNT composite sample was measured to be around four times lower than that of the pure copper sample. The average critical current-density–length threshold products of the pure Cu and Cu/CNT composites were estimated to be 1800 and 5400 A/cm, respectively. The slower EM rate of the Cu/CNT composite stripes is attributed to the presence of CNT, which acts as trapping centers and causes a decrease in the diffusion of EM-induced migrating atoms.**

***Index Terms*—Carbon nanotube (CNT), composite, electromigration (EM), interconnect.**

I. INTRODUCTION

As THE interconnect feature size shrinks by 30% in each technology node, the current density through the interconnect increases as the square of scaling factor [1]. Copper interconnect is becoming more and more vulnerable to the electromigration (EM) due to the high current density ($> 10^6$ A/cm^2). Impurity doping and tight capping have been reported as two effective approaches to improve the EM resistance of the copper interconnects [2], [3].

Barmak *et al.* [2] have arrived at a set of potential elements to improve the EM resistance of copper interconnects. Carbon is also listed as one of the elements. Carbon nanotube (CNT) has been demonstrated with excellent electrical and mechanical properties and extremely high EM resistance [4]–[6]. CNTs are considered as potential candidates for next-generation interconnects [5], [6]. However, there are still significant engineering problems to overcome [7]. In this letter, we used Cu as metal matrix and CNT as EM resistance reinforcement. We found that the Cu/CNT composite has much better EM resistance than the copper.

II. FABRICATION OF THE TEST STRUCTURE

We used the test structure developed by Blech here [8]. A schematic showing the cross section of the structure is shown in Fig. 1(a). A silicon wafer covered with 1-μm thermal oxide was used as a substrate. The Mo(2000 Å)/TaN(100 Å) bilayers were deposited onto the substrate, where Mo serves as a base conductor and TaN serves as a diffusion barrier. A 5-nm Ni catalyst for CNT growth was deposited on the Mo/TaN segment by e-beam evaporation. The substrate was loaded into a plasma-enhanced CVD system to grow the low-density CNTs. The copper deposited by electrochemical plating method can infiltrate to the bottom of the low-density CNTs, filling the voids between the nanotubes [9]. The thickness of the Cu/CNT composite is around 3500 Å. The Cu Blech samples were also fabricated as reference. All samples were annealed in a 15% H_2–85% N_2 mixture at 550 °C for 1 h.

III. RESULTS AND DISCUSSIONS

The resistivities of Cu and Cu/CNT composites are 1.9 and 2.2 $\mu\Omega \cdot$ cm, respectively, obtained from the van-der Pauw test structure fabricated on the same chip as the Blech test structure. The slightly larger resistivity of Cu/CNT composite is believed to come from carrier scattering at the interface phase. The resistivity of Cu/CNT composite is possibly further reduced by some process optimization. To avoid the oxygen corrosion of Cu film, we assembled the Blech test samples on a ceramic package filled with argon. Fig. 1(b)–(g) shows examples of the mass transport as a result of the EM of Cu and Cu/CNT as a function of the stressing time. The samples were stressed at a current density of 1.2×10^6 A/cm^2. The as-prepared Cu/CNT composite film without the polishing process has a roughness of about 100 nm. We observe that the copper segment drifted a significant percentage of the total length, whereas the Cu/CNT test structure had a nearly imperceptible void growth which was visible only under high magnification. After hundreds of hours of EM testing, small voids were formed and observed in the Cu/CNT stripe using high-magnification SEM. Unlike the edge depletion of the Cu stripe, the voids are randomly distributed along the Cu/CNT stripes. The copper atoms around the CNT showed no obvious void growth.

Fig. 2 shows the plot of the average void growth length (ΔL) versus stressing time for Cu and Cu/CNT samples. The Cu EM void growth rate (ΔL divided by stressing time t) can be obtained from the slopes of the best fitted line. The average void growth rate of Cu/CNT stripe is much smaller than that of the copper. For the Cu/CNT stripe, the void growth at the beginning

---

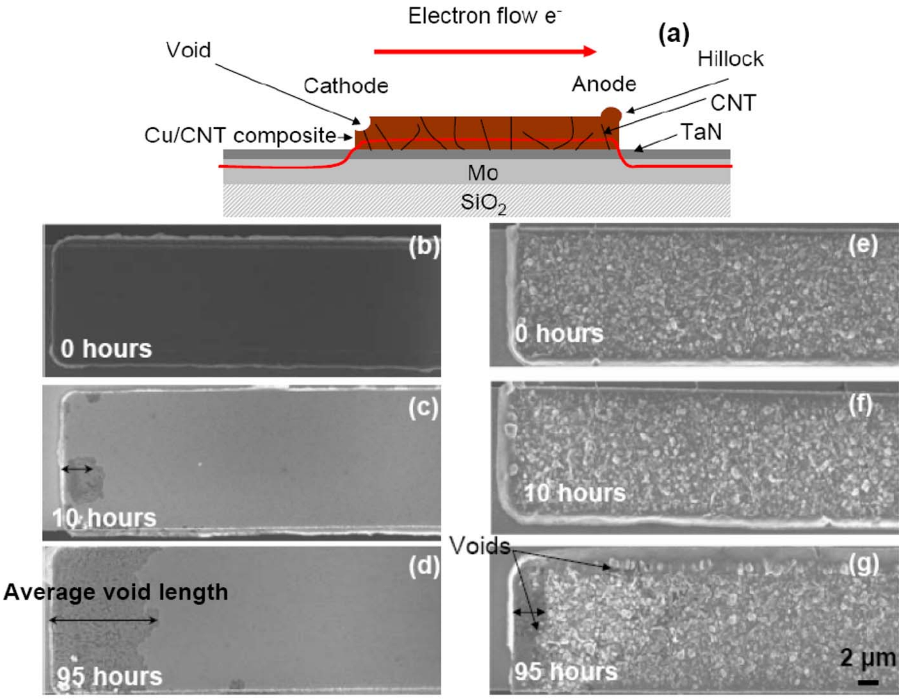
Manuscript received April 15, 2008. This work was supported in part by the Croucher Foundation under Grant CAS-CF05/06.EG01 and in part by the Research Grants Council of Hong Kong Competitive Earmarked Research Grant under Grant 611305. The review of this letter was arranged by Editor S. Kawamura.

Y. Chai, P. C. H. Chan, and Y. Fu are with the Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Kowloon, Hong Kong (e-mail: eeychai@ust.hk).

Y. C. Chuang and C. Y. Liu are with the Department of Chemical and Materials Engineering, National Central University, Taoyuan 320, Taiwan, R.O.C.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2008.2002075



Pure copper stripes

Copper/CNT composite stripes

Fig. 1. (a) Schematic diagram of the Blech test structure for EM testing. SEM images of the cathode end of (b)–(d) pure copper and (e)–(g) copper/CNT composite segments after a series of EM testing. The data came from the 150-μm-long and 12-μm-width test stripes.

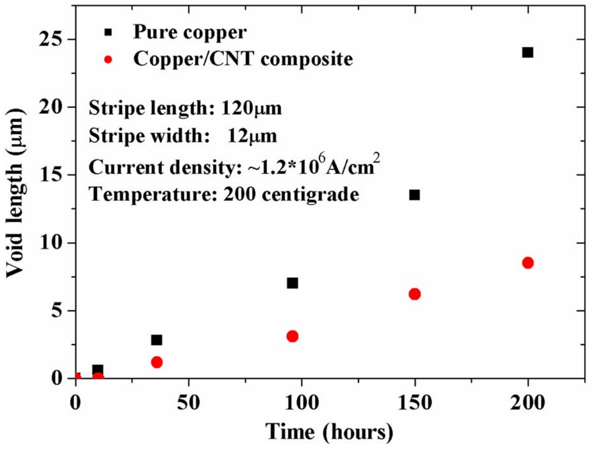


Fig. 2. Plots of void growth length as a function of the stressing time for pure Cu and Cu/CNT composite stripes.

is almost unnoticeable, as shown in Fig. 3(b). The average void growth rate of the Cu/CNT is about four times lower than that of the copper. In the equal EM depleted length, the Cu/CNT stripe has much lower depleted area than that of the copper. Therefore, we expect that the lifetime of the Cu/CNT composite is more than four times that of the copper.

The mass transport in a finite-length stripe will deplete the material at cathode and accumulate at the anode. The material accumulated at the anode generates a compressive stress gradient which retards the EM flux. The threshold product of current density and a critical length emerges [8], below which the net mass transport of materials vanishes. Fig. 3(a) and (b) shows

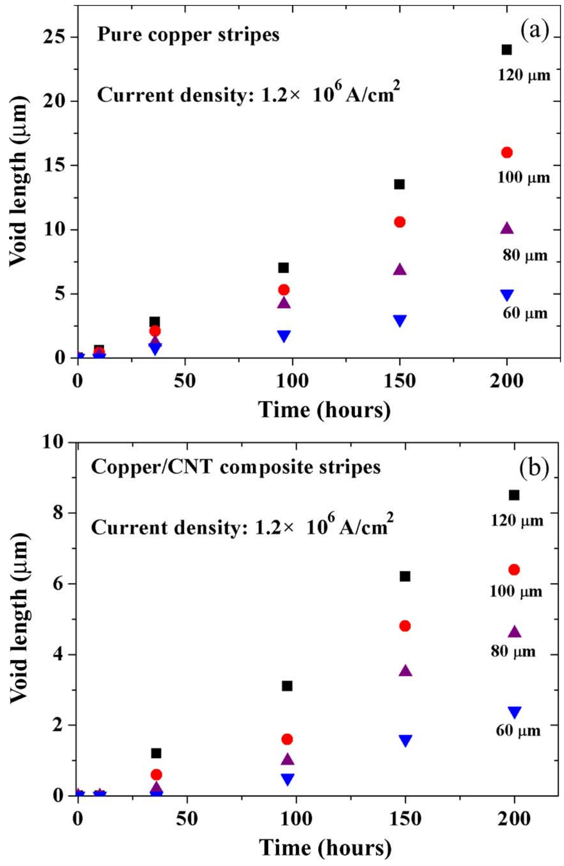


Fig. 3. Plot of void growth length versus stressing time for (a) pure Cu and (b) Cu/CNT composite stripes with different lengths (60, 80, 100, and 120 μm) and 12-μm width.

plots of void length as a function of stressing time of the Cu and Cu/CNT stripes with different lengths. The longer stripe shows larger void length, whereas almost no void formation in the stripes below 50 μm for Cu/CNT and 20 μm for Cu was observed. These results suggest that there is a critical length effect in shorter length stripe where the EM flux is balanced by the backflow generated by the stress gradient. The critical lengths of the stripe were measured to range between the longest segment without void growth and the shortest segment with void growth. The critical current-density–length threshold products of the Cu and Cu/CNT composites are estimated to be 1200–2400 and 4800–6000 A/cm, respectively.

The hydrogen plasma atmosphere during PECVD process created a rough sidewall on the CNT. A strong mechanical interlocking at the rough CNT sidewalls resulted in high bonding strength between CNT and Cu [10]. Assuming that the tensile stress caused by EM is transferred to nanotube via a nanotube-matrix interfacial shear mechanism [11], a force-balance-based expression for the nanotube-Cu interfacial shear strength τ_{CNT} may be derived as follows:

$$\tau_{\mathrm{CNT}} = \frac{\sigma_{\mathrm{CNT}}}{2(l/D)} \tag{1}$$

where σ_{CNT} is the strength of the CNT, and l ($\sim$1 μm) and D ($\sim$20 nm) are the length and the diameter of the CNT, respectively. The strength of the CNT was reported to be around 150 GPa [11]. The interfacial shear strength τ_{CNT} is calculated to be around 1.5 GPa, which is much higher than the tensile stress for migrating the copper atoms σ_{Cu} ($\sim$230 MPa) [12], significantly reducing the Cu EM flux along the nanotube.

The EM failure at the interface is caused by the delamination between the metal conductor and the surrounding material. The failure criterion is that the strain energy released by the delamination exceeds the energy required to form the two new surfaces [13]. Delamination occurs when the strain energy exceeds the adhesion energy G_{adh}. The maximum stress could be calculated from

$$\sigma_{\mathrm{delam}} = \sqrt{\frac{2E_n G_{\mathrm{adh}}}{h}} \tag{2}$$

where σ_{delam} is the stress normal to the plane of the delamination, E_n is the elastic modulus of the conductor, and h is the thickness of the conductor [13]. In the Cu/CNT composites, the CNTs were grown on the catalyst layer, as shown schematically in Fig. 1(a). The as-grown CNT has strong chemical bonding to the seed particles, which is believed to improve the adhesion G_{adh}. The elastic modulus of the Cu/CNT has also been measured to be around three times larger than that of the copper [14]. Owing to the larger σ_{delam} and better bonding G_{adh} of the Cu/CNT, the EM resistance of copper is enhanced accordingly.

IV. CONCLUSION

The average EM void growth rate of the Cu/CNT composite is about four times smaller than that of the copper. The threshold product is estimated to be around three times larger than that of the copper. The slower EM rate of the Cu/CNT stripes is attributed to the presence of CNTs, decreasing the diffusivity of the EM-induced migrating atoms. These results suggest that Cu/CNT is potentially a good candidate for advanced interconnect applications where high electrical conductivity and good EM resistance are required.

REFERENCES

[1] International Technology Roadmap for Semiconductors, San Jose, CA: Semicond. Ind. Assoc., 2005.

[2] K. Barmak, C. Cabral, K. P. Rodbell, and J. M. E. Harper, "On the use of alloying elements for Cu interconnect applications," *J. Vac. Sci. Technol. B, Microelectron. Process. Phenom.*, vol. 24, no. 6, pp. 2485–2498, Nov. 2006.

[3] C. K. Hu, L. M. Gignac, R. Rosenberg, B. Herbst, S. Smith, J. Rubino, D. Canaperi, S. T. Chen, S. C. Seo, and D. Restaino, "Atom motion of Cu and Co in Cu damascene lines with a CoWP cap," *Appl. Phys. Lett.*, vol. 84, no. 24, pp. 4986–4988, May 2004.

[4] B. Q. Wei, R. Vajtai, and P. M. Ajayan, "Reliability and current carrying capacity of carbon nanotubes," *Appl. Phys. Lett.*, vol. 79, no. 8, pp. 1172–1174, Aug. 2001.

[5] J. Li, Q. Ye, A. Cassell, H. T. Ng, R. Stevens, J. Han, and M. Meyyappan, "Bottom-up approach for carbon nanotube interconnects," *Appl. Phys. Lett.*, vol. 82, no. 15, pp. 2491–2493, Apr. 2003.

[6] Q. Ngo, A. M. Cassell, A. J. Austin, J. Li, S. Krishnan, M. Meyyappan, and C. Y. Yang, "Characteristics of aligned carbon nanofibers for interconnect via applications," *IEEE Electron Device Lett.*, vol. 27, no. 4, pp. 221–224, Apr. 2006.

[7] Y. Chai, K. Zhang, M. Zhang, P. C. H. Chan, and M. M. F. Yuen, "Carbon nanotube/copper composites for via filling and thermal management," in *Proc 57th Electron. Compon. Technol. Conf.*, Jun. 2007, pp. 1224–1229.

[8] I. A. Blech and E. Kinsbron, "Electromigration in thin gold-films on molybdenum surfaces," *Thin Solid Films*, vol. 25, no. 2, pp. 327–334, Oct. 1975.

[9] Q. Ngo, B. A. Cruden, A. M. Cassell, G. Sims, M. Meyyappan, J. Li, and C. Y. Yang, "Thermal interface properties of Cu-filled vertically aligned carbon nanofiber arrays," *Nano Lett.*, vol. 4, no. 12, pp. 2403–2407, Nov. 2004.

[10] S. B. Lee, K. Matsunaga, Y. Ikuhara, and S. K. Lee, "Effect of alloying elements on the interfacial bonding strength and electric conductivity of carbon nano-fiber reinforced Cu matrix composites," *Mater. Sci. Eng., A*, vol. 449–451, pp. 778–781, Jan. 2007.

[11] H. D. Wagner, O. Lourie, Y. Feldman, and R. Tenne, "Stress-induced fragmentation of multiwall carbon nanotubes in a polymer matrix," *Appl. Phys. Lett.*, vol. 72, no. 2, pp. 188–190, Jan. 1998.

[12] D. W. Gan, P. S. Ho, R. Huang, J. Leu, J. Maiz, and T. Scherban, "Isothermal stress relaxation in electroplated Cu films. I. Mass transport measurements," *J. Appl. Phys.*, vol. 97, no. 10, pp. 103 531-1–103 531-8, May 2005.

[13] J. R. Lloyd, C. E. Murray, T. M. Shaw, M. W. Lane, X. H. Liu, and E. G. Liniger, "Theory for electromigration failure in Cu conductors," in *Proc. 8th Int. Workshop Stress-Induced Phenomena Metallization*, Sep. 2006, pp. 23–33.

[14] T. J. Kang, J. W. Yoon, D. I. Kim, S. S. Kum, Y. H. Huh, J. H. Hahn, S. H. Moon, H. Y. Lee, and Y. H. Kim, "Sandwich-type laminated nanocomposites developed by selective dip-coating of carbon nanotubes," *Adv. Mater.*, vol. 19, no. 3, pp. 427–432, Feb. 2007.