교류전류 주파수 및 절연층에 따른 배선의 열피로 손상에 대한 실시간 분석
(*In-situ* analysis on interconnect fatigue damages due to AC frequencies and overlayer)

박영배, R. Moenig*
안동대학교 신소재공학부, * MIT 재료공학과

Abstract

Although it was recently observed that severe fatigue damage was formed in Al or Cu interconnects due to the cyclic temperatures generated by Joule heating of the metal lines by the passage of alternating currents (AC) (see Fig. 1), AC loading frequency effect on the damage evolution characteristics are not known so far. This work focused on the effect of AC loading frequency (100 Hz vs. 10 kHz) on the thermo-mechanical fatigue characteristics and its relationship with the Cu microstructures by using polycrystalline sputtered Cu lines (200 to 300 nm thick and 8 um wide) on Ta with temperature cycles with amplitudes from 100 to 300°C (see Fig. 2). It was consistently observed that higher loading frequency accelerated damaged grain growth and led to earlier failure irrespective of Cu grain sizes. This frequency effect, that is, extensive surface damage evolution at higher frequencies, were apparent at higher ΔT (>160°C) and disappeared at lower ΔT (<130°C) (see Fig. 3). It was also found that there was a strong constraint effect on dislocation activities and surface damage evolutions by the smaller grain sizes which might result in more fatigue resistant. Severe fatigue damages were formed in Cu lines during temperature cycling by alternating current, and the larger temperature amplitude led to the shorter failure cycles which implied that alternating current could be used to perform thermo-mechanical fatigue test of metal interconnect.

(100) grains generated the extensive facetted grain growth by consuming neighboring twin and grain boundaries and had the long, parallel, and evenly distributed wrinkles which were preferentially arrayed in close (100) orientation where boundary segments were aligned in close 45o tilted from metal line direction and also aligned in (110) orientation which is parallel to the slip trace direction of (111) plane. The repetitive dislocation glide on (111) plane inside (100) grain by the maximum resolved shear stress under the close uniaxial stress state to the line direction during so fast cyclic loading were thought to result in this characteristic boundary configuration which seemed to be a general characteristic of grain boundary migration of metal fatigued at high temperatures.

(111) grains generated different types of damage such as grooving and thinning near

grain and twin boundaries and spherical void formation along twin boundaries which seemed to be related to the diffusion-controlled processes.

Higher loading frequency accelerated damaged grain growth at higher ΔT (>160°C) and led to earlier failure irrespective of Cu grain sizes. Possible mechanisms for this result were proposed by thermally activated strain rate-dependent dislocation activities or by a competition between the repetitive dislocation glide dependent on the fatigue stress cycle and the damaged grain shrinkage by diffusion process in order to minimize the free energy of the system which depend on diffusion time or length scale during each cycle or total cycles. But further work is needed to understand in more detail the possible mechanism on this frequency effect. Frequency dependence of fatigue behavior and also damage evolution itself were suppressed at low temperature ranges (ΔT<130°C) which is a general mechanical fatigue behavior of f.c.c. metal, that is, no loading frequency effect for mechanical fatigue at room temperature.

Figure 4 shows the number of cycles to failure for a given applied temperature amplitude of 10nm Ta/200nm Cu line with and without soft passivation materials after AC testing at 10kHz frequency, which showed typical fatigue behavior and so alternating current could be used to perform thermo-mechanical fatigue test of interconnect. Soft passivation does not change fatigue lifetime, damage extent and morphology. Therefore, fatigue can be a reliability threat to Cu interconnects with soft low-k dielectrics.

References

[1] C. A. Volkert, R. Moenig, Y. B. Park, and G. P. Zhang, *Mat. Res. Soc. Spring Meeting*, Symposium E: Materials, Technology, and Reliability for Advanced Interconnects and Low-k Dielectrics (2003).

[2] Y. B. Park, R. Moenig, and C. A. Volkert, International Workshop on Stress-Induced Phenomena in Metallization (2004)

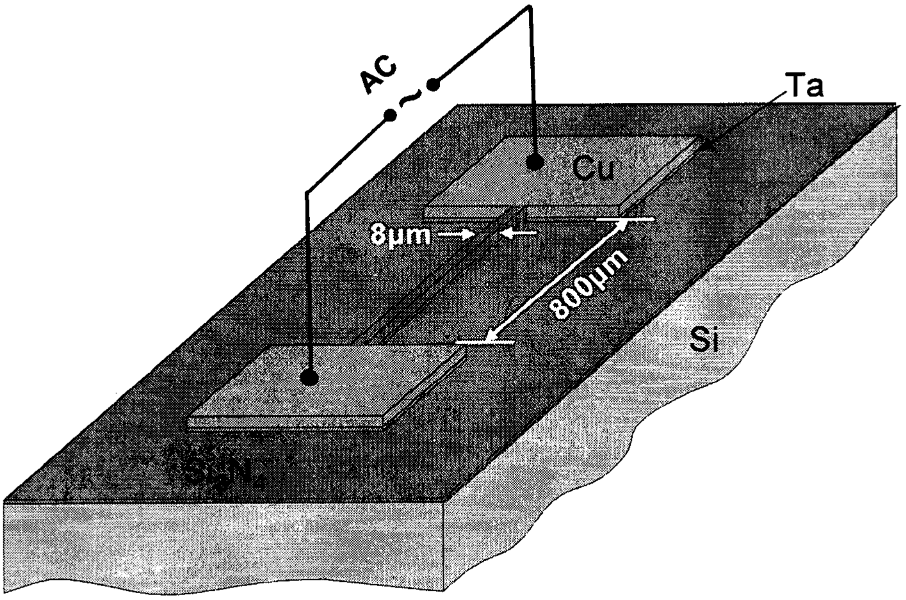

Fig. 1. Schematic of the sample structure used for thermo-mechanical fatigue testing by AC.

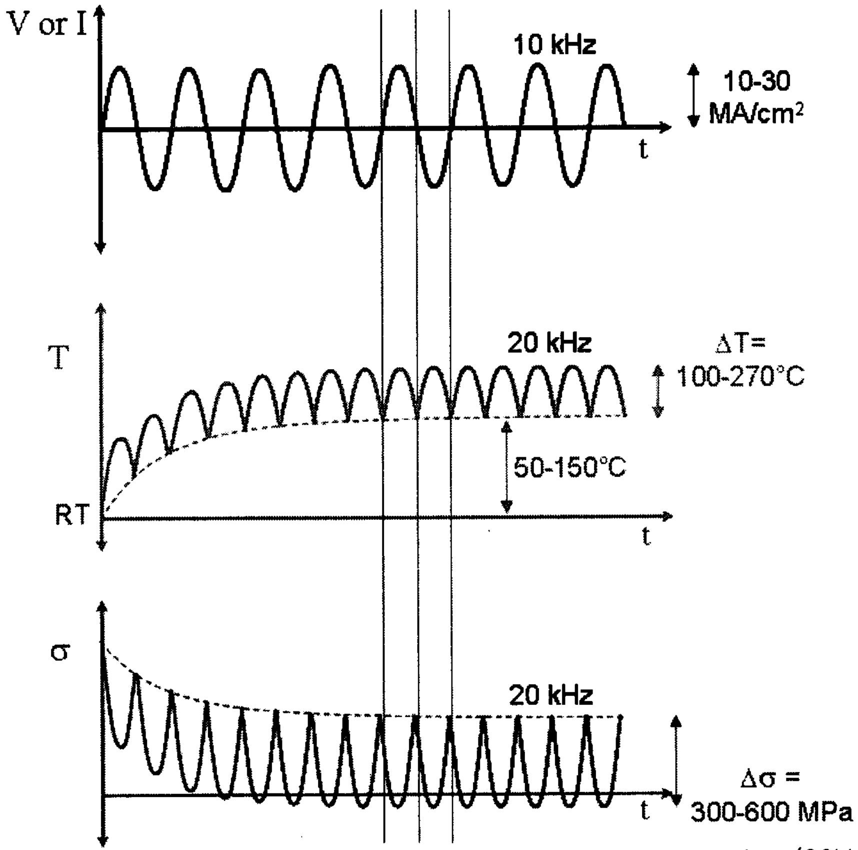

Fig. 2. Schematic on the concept of thermo-mechanical stress cycles (20kHz) by pure AC cycles (10kHz)

Fig. 3. Loading frequency effect of coarse-grained 10nm Ta/200nm Cu lines; damaged area fraction (DAF) comparisons between 100Hz and 10kHz for the same ΔT and cycles. Here, each cycle number means the failure cycles of 10kHz test at each ΔT except for ΔT = 130°C which was stopped before failure. Testing with 100Hz was stopped without open failure at the failure cycles of 10kHz. DAF was defined as total damaged area observed from SEM pictures of whole metal line divided by the whole metal line area.

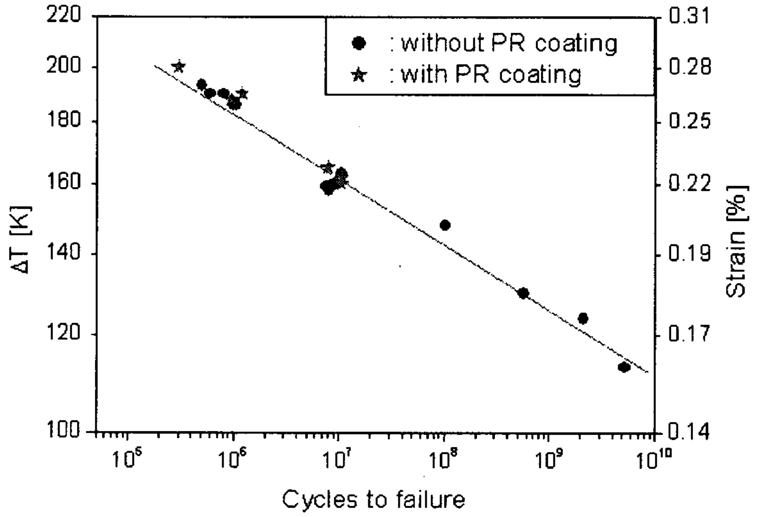

Fig. 4. Number of cycles to failure at various applied temperature amplitudes for 10nm Ta/200nm Cu line with and without PR (Photoresist) overcoating after AC testing at 10kHz frequency.