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Effects of Temperature Amplitude and Loading Frequency on Alternating Current - Induced Damage in Cu Thin Films

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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), 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 by using polycrystalline sputtered Cu lines with temperature cycles with amplitudes from 100 to 300°C. It was consistently observed that higher loading frequency accelerated damaged grain growth and led to earlier failure irrespective of Cu grain sizes. The frequency effect is believed to result from differences in the concentration of defects created by the deformation-induced motion of dislocations to the grain boundaries.

Keywords: Fatigue, Alternating current, Frequency effect, Metal interconnect

1. Introduction

Metal interconnects in microelectronic devices are subjected to a wide variety of time-varying mechanical loadings caused by the temperature cycling due to the power changes during normal operation, which can be a serious long-term reliability threat of the electronic systems. It was reported 30 years ago[1)] that alternating current-induced thermal strains could lead to surface damage associated with slip band formation in unpassivated wide (25 μm) Al lines with 1 μm thickness. These thermal strains arose during the application of time-varying currents to metal interconnects because of the thermal mismatch of the metal interconnect with Si substrate during temperature changes caused by Joule heating of interconnects itself, which can eventually lead to fatigue damage evolution and electrical failure of the metal interconnect. It has been recently observed that severe damage was formed in Al and Cu interconnects due to the passage of cyclic alternating currents at a frequency of 100 Hz[2,3)]. This damage was not due to electromigration but was caused by thermo-mechanical fatigue from the cyclic temperatures generated by Joule heating of the metal lines. Details on the experimental methods and the general damage evolution mechanisms by applying AC current at a frequency of 100 Hz were extensively reported in references[2,4)].

By the way, loading frequency effect on damage formation in Cu interconnect is a great interest for both technological and fundamental aspects. High performance microelectronic devices are continuously using higher frequencies to meet the faster speed which might lead to interconnect damage of new type when compared to the lower frequency devices. Even though there is a remarkable reduction in testing time for the very high cycle test regime by using higher loading frequency, there is a fundamental concern on any changes or influences in fatigue process by increase of cycling frequency. It has been reported[4-7)] that variations of loading frequency

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between 60 Hz and 20 kHz did not affect fatigue lifetimes for f.c.c. metals like Cu while pure b.c.c. metals were more frequency sensitive, that is, higher frequency testing led to prolonged fatigue lifetimes and higher mean endurance limits for b.c.c. metals. While most of reported results on loading frequency effects[4-7)] were focused on mechanical fatigue testing with bulk metals at room temperature, reports on the investigations of loading frequency effects in thermo-mechanical fatigue of the very thin (100~300 nm thick) metal interconnect systems were scarce. Thermal cycle loading on thin metal line will show very different loading frequency influences from the reported results[4-7)].

In this work, the effects of loading frequency on the formation of thermal fatigue damage in 200 nm thick Cu interconnects were investigated. Although frequency effects have not been observed in the fatigue behavior of bulk fcc metals[4-7)], there are reasons to expect that they may be important in structures with small dimensions. In particular, it has been observed that when Cu film thicknesses approach 100 nm, the mechanism controlling fatigue damage formation changes from a dislocation glide process to a diffusion mediated process[3,8,9)]. When diffusion is active during fatigue, then the loading frequency may play a role.

2. Experimental

Single-level test structures (Fig. 1) were fabricated using conventional film deposition and patterning methods. First <100> Si wafers with 50 nm of SiO_2 and 50 nm of amorphous silicon nitride were coated with e-beam resist and patterned by electron beam lithography. 10 nm Ta and 200 nm Cu films were sequentially deposited on the patterned substrates without a vacuum break using a DC magnetron sputtering system. After dissolving the resist, metal line structures with length of 800 μm and width of 8 μm were formed. Then the samples were annealed for 15h at 400°C in vacuum ($<10^{-6}$ mbar), to allow for grain growth. The grain size and microstructure of the annealed Cu structures were characterized by scanning electron microscopy (SEM) with back-scattered electron imaging and focused ion beam microscopy. AC test was conducted *in-situ* at a vacuum ($<10^{-5}$ mbar) in a SEM in which sample was attached to a probe stage using silver paste and the bonding pads connected by 4 needle probes to the electronics outside. Electrical stressing was performed at room temperature using a pure sinusoidal applied voltage (DC offsets less than several mV) with rms current densities of 10 to 40 MA/cm^2 at frequencies of 100 Hz and 10 kHz. Temperature of metal line was monitored during AC test by measuring time-resolved 4 point resistance of interconnect. It was assumed that measured temperature is nearly uniform along the whole length of long metal line during each short cycle by neglecting edge effects, which were confirmed by finite element analysis[3)]. By the limitation on heat dissipation capability through probe stage, sample holder, and SEM chamber for our high frequency regimes, average temperature of Cu line increased continuously for a few minutes (lightly depends on the magnitude of applied frequency and voltage) and then reached a constant value until it (or resistance) rapidly increased just before failure occurred by open circuit.

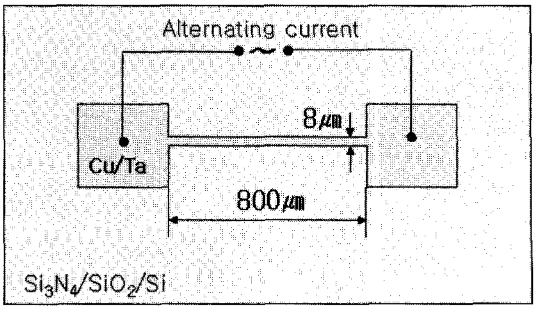

Fig. 1. Schematic of the sample structure used for thermo-mechanical fatigue testing by AC.

The cyclic change in temperature resulted in cyclic strain in the Cu line due to the thermal expansion mismatches between the Cu line and Si substrate. Average stress of 200 nm Cu film measured by

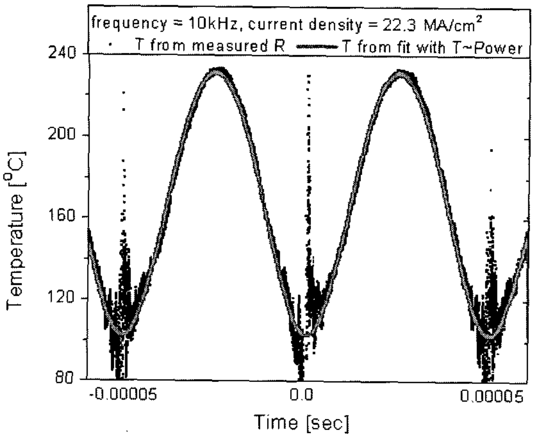

Fig. 2. Measured (dot point) and fitted (solid line) temperatures at rms current density of 22.3 MA/cm^2 and frequency of 10 kHz [9].

wafer curvature method implied that temperature cycle of 100~270°C would generate stress cycle of 300~600 MPa in Cu film[3,8,9]. Temperature obtained by measured resistance was best fitted by the fitting line which was obtained by assuming that instantaneous temperature (or, resistance) is proportional to the instantaneous power values[3,8,9]. For example, current (or, voltage) cycle of 10 kHz with rms current density of 22.3 MA/cm^2 generated temperature cycle (ΔT) of 130°C with frequency of 20 kHz, as shown in Fig. 2[9].

Each of $\Delta T = 130$, 160, and 190°C was applied during the same cycles for both frequencies of 100 Hz and 10 kHz to investigate the effect of frequency on damage evolution characteristics at the same ΔT and cycles. The same cycle number for both frequencies at each ΔT was chosen as the shorter failure cycle number between the two frequencies. Differences of absolute temperature values between 100 Hz and 10 kHz for the same ΔT were relatively small for the ΔT ranges used in this experiment, for example, less than 10°C for $\Delta T = 190$°C. Grain size and microstructure were characterized by SEM back-scattered electron (BSE) imaging and focused ion beam (FIB) microscopy. Textures of Cu films were investigated by standard X-ray diffraction (XRD) method. Local information on grain orientation was obtained by electron backscatter diffraction (EBSD) and inverse pole figure (IPF).

3. Results

During thermal fatigue testing, damaged regions were observed to form along the length of the Cu lines. The damage was typically more extensive and severe in the middle of the lines, presumably because this region experienced somewhat larger temperature swings[8,9]. Within many of the damaged regions, clearly defined and regularly spaced surface extrusions were found, which are similar to those which develop due to irreversible slip at the surfaces of mechanically-fatigued Cu[10]. *In-situ* SEM observations showed that the number and size of the damaged regions and the amplitude of the surface roughness increased as testing progressed. Eventually, cracks formed at damaged locations where the film was thinnest and propagated across the line width, leading to resistance increases, localized melting, and open circuit failure. Details on the general damage evolution characteristics of Cu line by applying alternating current at a frequency of 100Hz were reported in ref. 4.

In order to investigate the effect of loading frequency on damage evolution, the damaged area fractions (DAF) under different loading conditions were compared. The damaged area fraction is defined as the total damaged area in a given line divided by the entire line area. Results of a comparison test are shown in Fig. 3 and 4. Similar thermal loads were applied to the two samples ($\Delta T = 190$ or 195°C), for the same number of cycles (8.0×10^5), but at different loading frequencies (100 Hz vs. 10 kHz). The sample tested at 100 Hz exhibited a DAF of only 0.2% (only two damaged grains were found in the entire metal line), but the sample tested at 10 kHz had a DAF of 20%, at which point it failed by an electrical open. A clear increase in DAF with loading frequency is seen except at the lowest ΔT of 130°C. The effect of frequency on accelerating damage formation is clearest for the largest ΔT, which

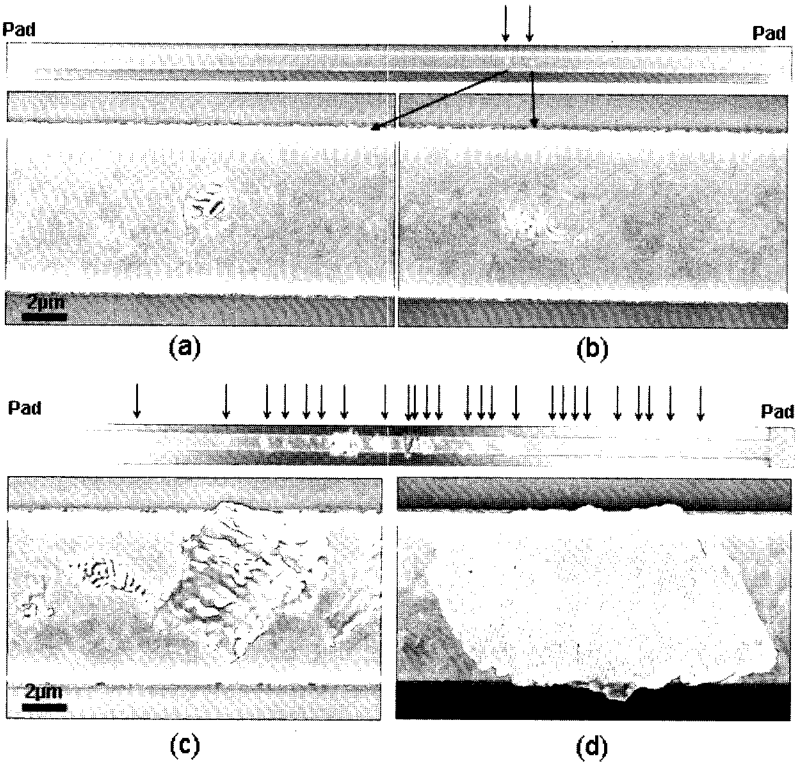

Fig. 3. SEM pictures of tested whole metal lines (upper long lines) and of representative damage morphologies (lower damage pictures) for $\Delta T = 190°C$ by applying (a), (b) 100 Hz and stopped at 8.0×10^5 cycles with 0.2% DAF, and (c), (d) 10 kHz and failed at 8.0×10^5 cycles with 20% DAF. Here, damaged area fraction (DAF) was defined as total damaged area observed from SEM pictures of whole metal line divided by the whole metal line area. Each arrow in upper line means each damage location in whole metal line.

corresponds to the largest applied strain and to the highest temperatures. In two of the samples tested at 10 kHz failure occurred at the listed cycle number while none of the samples tested at 100 Hz had failed. As expected for fatigue testing, the number of cycles to failure increased with decreasing load. Not only the development of damage, but also the number of cycles to failure is accelerated by raising the loading frequency. The samples that show the frequency effect most clearly ($\Delta T = 190$ or 195°C) experienced only a small difference in average temperature of around 12°C. The loading frequency not only affected the amount of damage that was formed, but also affected the nature of the damage. The lines tested at 10 kHz exhibited large, facetted damaged regions associated with <100> grains, much more often than those tested at 100 Hz. The lines

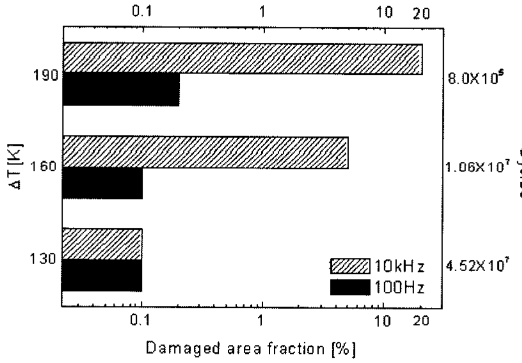

Fig. 4. Effect of temperature range and loading frequency (100 Hz and 10 kHz) on number of cycles and DAF. Here, each cycle number means the failure cycles of 10 kHz test at each ΔT except for $\Delta T = 130°C$ which was stopped before failure. Testing with 100 Hz was stopped without open failure at the failure cycles of 10 kHz.

tested at 100 Hz typically showed deep grooves near grain and twin boundaries, characteristic of damaged <111> out-of-plane oriented grains. Only when ΔT was larger than 200°C did Cu lines tested with 100 Hz exhibit large damaged <100> grains, and even then they were smaller than those observed after testing at 10 kHz with the same ΔT and cycle number.

4. Discussions

Fig. 3 and 4 clearly showed that higher loading frequency accelerated damaged grain growth and eventually led to earlier failure. This frequency effect seemed to be a general phenomenon for thermo-mechanical fatigue of thin Cu film irrespective of microstructure.

It was reported4-7) that variations of loading frequency between 60 Hz and 20 kHz did not affect fatigue lifetimes for f.c.c. metals like Cu while b.c.c. metals were more frequency sensitive, that is, higher frequency testing led to prolonged fatigue lifetimes and higher mean endurance limits for b.c.c. metals. Two main mechanisms that characterize the loading frequency dependence of the fatigue behavior of b.c.c. metals were known as the thermally activated glide of screw dislocations which is limited at higher strain rates due to lattice friction stresses resulting in higher flow stresses11) and a homogenization of deformation resulting in longer lifetimes at higher frequencies as shown in ref. 25 for polycrystalline α-iron. Most works4-7,11,12) on the loading frequency effect were carried out on the pure mechanical fatigue of bulk metal at room temperature.

Our experiment is a thermo-mechanical fatigue induced by alternating current for very thin (200~300 nm thick) Cu lines with the temperature cycle ranges between 130°C~300°C and with the minimum temperature values during each cycle between 50°C~150°C which depend slightly on the applying frequency and largely on the applying voltage3,8,9). There was little damage formation for T less than about 130°C at both frequencies and indistinguishable between two frequencies, which looked like similar with bulk Cu fatigued mechanically at room temperature4). Frequency dependence of fatigue behavior was suppressed at low temperature ranges which led to the general mechanical fatigue behavior of f.c.c. metal, that is, no loading frequency effect4,5).

In our experiments, the effect of frequency is opposite to what is observed in bcc metals – namely increasing the frequency accelerates damage formation in the thin Cu films rather than delaying it. The magnitude of the frequency effect increases with the imposed thermal strains and temperature ranges. However, in these tests an increase in temperature range also corresponds to an increase in average temperature, so it is not clear if the frequency effect is enhanced by temperature or by increased plastic strain. In any case, the fact that a frequency effect is not observed in bulk fcc metals at room temperature indicates that the effect observed here is either due to the small sample dimensions or to the elevated temperatures.

The higher fraction of damaged area on increasing the frequency is predominately due to the enhanced formation of damaged <100> grains. Thus, the increased loading frequency somehow enhances the deformation-induced grain growth process. One possible explanation for this effect is that grain boundary mobility is increased by the glide of dislocations to the boundaries. The incorporation of dislocations in the boundaries creates defects that increase the boundary mobility. The effectiveness of the defects in raising the boundary mobility will depend on the active slip systems – and thus on the grain orientation – and on the orientation of the grain boundaries. Therefore, preferred orientations of growing grains and facetted boundaries can be expected. Raising the loading frequency or strain rate would increase the rate of defect creation in the boundaries. Raising the temperature would increase the boundary mobility and increase the rate at which the deformation-induced boundary defects can annihilate. Depending on the activation energies for these different processes, it is possible to find intermediate temperature ranges where there is a clear enhancement of boundary mobility by deformation.

Severe surface damages of Cu line were developed at high temperature cycling conditions due to the relief of stresses induced by the thermal expansion mismatch between metal interconnect and Si substrate during temperature changes. This surface damage evolution can cause serious reliability concerns because roughened surface can increase sheet resistance, and the very thin regions which develop between each wrinkle can cause higher current density which promote electromigration or even local heating and electrical open failure of metal interconnect. Also, extrusions at boundary or inside of the damaged region (cf. Fig. 3(c)) can punch through the soft low-k inter-level dielectrics in multilevel metallization structure and presumably lead to interlayer electrical shorts similarly with hillocks in electromigration phenomena. Hard inter-level dielectrics like chemical vapor deposition silicon dioxide presumably hinder this kind of surface damage evolution while soft low-k dielectrics extensively adopted recently may not retard it[8,9].

5. Conclusions

The effect of loading frequency on thermal fatigue damage in 200 nm thick polycrystalline sputtered Cu lines on Si substrates has been investigated. A strong influence of loading frequency on the damage morphology and fatigue lifetime was observed either due to the small sample dimensions or to the elevated temperatures. The occurrence of deformation-induced growth of <100> out-of-plane oriented grains was greatly enhanced at the higher frequencies. This observation could be explained in terms of the enhancement of grain boundary mobility by the glide of dislocations to the boundaries as the incorporation of dislocations in the boundaries creates defects that increase the boundary mobility.

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References

1. E. Philofsky, K. Ravi, K. Hall, and J. Black, “Surface Reconstruction of Aluminum Metallization-a New Potential Wearout Mechanism,” *9th Annual Proceedings of Reliability Physics*, IEEE, New York, 120 (1971).
2. R. R. Keller, R. Mönig, C. A. Volkert, E. Arzt, R. Schwaiger, and O. Kraft, “Interconnect Failure due to Cyclic Loading”, AIP Proceedings of the 6th International Workshop of Stress Induced Phenomena in Metallization, edited by S. P. Baker, M. A. Korhonen, E. Arzt, P. S. Ho (AIP, Melville, NY, 2002) 119.
3. R. Mönig, R. R. Keller, and C. A. Volkert, “Thermal fatigue testing of thin metal films”, Rev. Sci. Instrum, 75, 4997 (2004).
4. H. Mayer, “Fatigue crack growth and threshold measurements at very high frequencies”, Int. Mat. Rev. 44, 1 (1999).
5. M. Papakyriacou, H. Mayer, C. Pypen, H. Plenk Jr., and S. Stanzl-Tschegg, “Influence of loading frequency on high cycle fatigue properties of b.c.c. and h.c.p. metals”, Mat. Sci. Eng. A 308, 143 (2001).
6. H. Mayer and C. Laird, “Influence of cyclic frequency on strain localization and cyclic deformation in fatigue”, Mat. Sci. Eng. A 187, 23 (1994).
7. H. Mayer and C. Laird, “Frequency effects on cyclic plastic strain of polycrystalline copper under variable loading”, Mat. Sci. Eng. A 194, 137 (1995).
8. Y. B. Park, R. Moening and C. A. Volkert, “Frequency and Passivation Effects on AC- Induced Damage in Cu Line”, International Stress Workshop on Stress-Induced phenomena in Metallization (2004).
9. Y. B. Park, “Effect of Mcrostructure on Alternating Current-induced Damage in Cu Lines”, Journal if the Microelectronics and Packaging Society, 12, 27 (2005).
10. C. Hu, “Reliability phenomena under AC stress”, Microelectron. Reliab. 38, 1 (1998).
11. H. Mughrabi, K. Herz, and X. Stark, “Cyclic deformation and fatigue behaviour of α-Iron mono- and polycrystas”, Int. J. Fract. 17, 193 (1981).
12. S. I. Hong and C. Laird, “Control of fatigue crack initiation mode and fatigue life of α-Iron”, Mater. Sci. Eng. A 110, L23 (1989).