Electromigration Failure in Au and Joule Heating Induced Oxidation in Cu Conductors - Part 3

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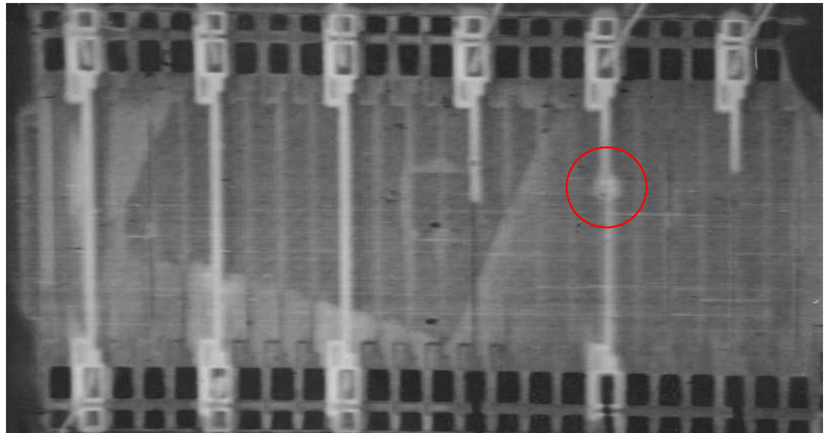
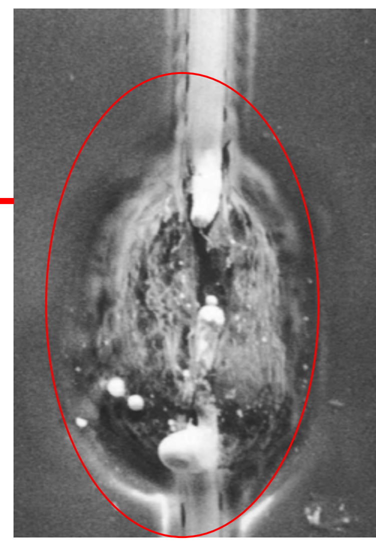
<u>Failure mode 3</u>: Here current continuity is still obtained, however, the leakage current across the polymer (sandwiched between Au and permalloy) is very large.

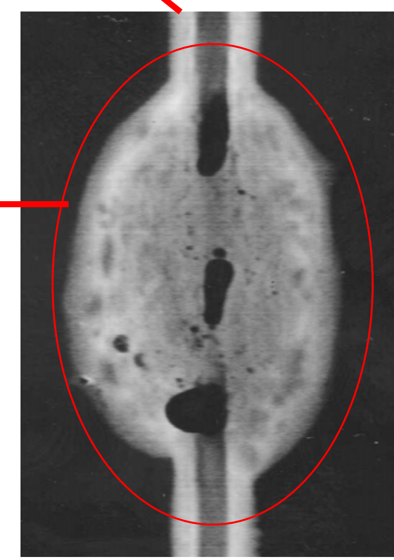


R1 through R6 at 15x, 20 kV, secondary electron mode

R2 void at 400x, 20 kV, backscattering mode



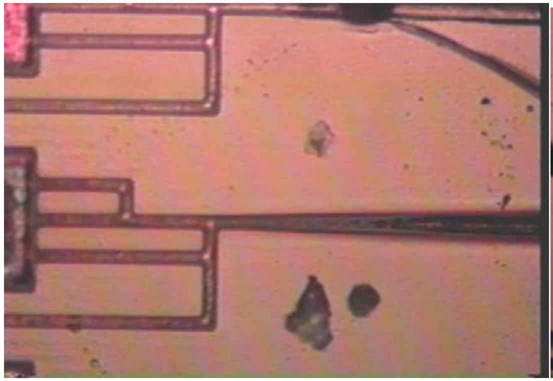
R2 void at 400x, 20 kV, secondary electron mode



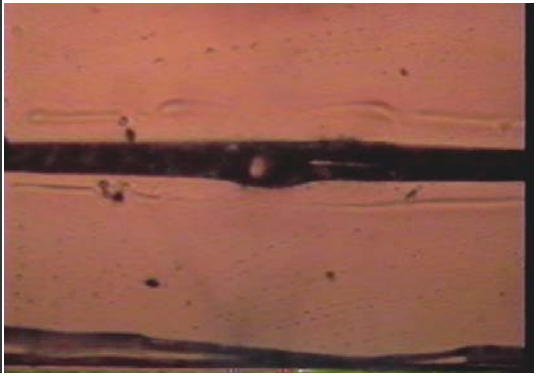
R2 void at 400x, 20 kV, EBIC mode

Oxidation in Cu Conductors due to Joule heating:

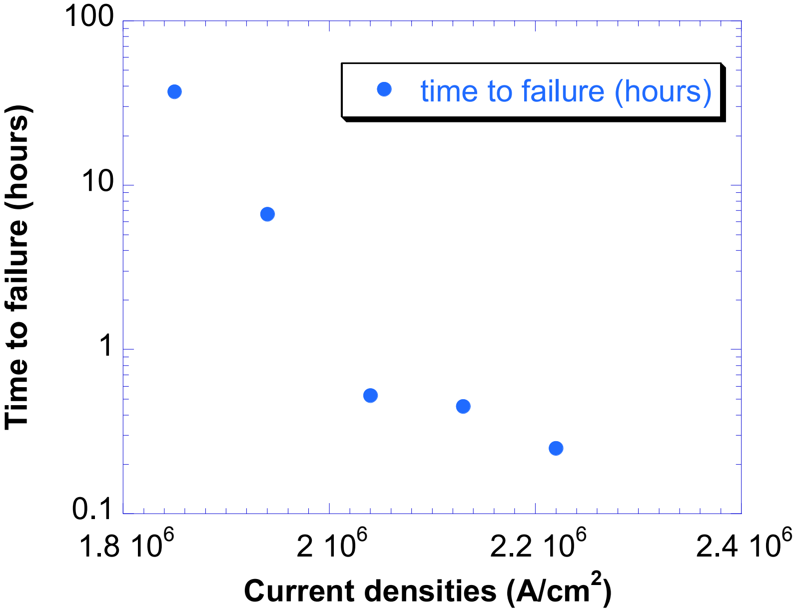
Using two probes at 60°C, our experiments show that Cu conductors failed in less than 7 hours at the following current densities: 2.13 x 10^6, 2.07 x 10^6, 2.03 x 10^6, 1.9 x 10^6 and 1.85 x 10^6 Amp/$cm^{2.}$ Joule heating occurred for all these values of current density. This can be clearly observed in the middle of the line, which deteriorated the polymer and exposed the lines to atmosphere. Since the Cu lines were exposed, they turned rapidly dark due to fast oxidation of Cu in air.



Joule heating and Oxidation of Cu at 2.1 x 10^6 A/cm^2

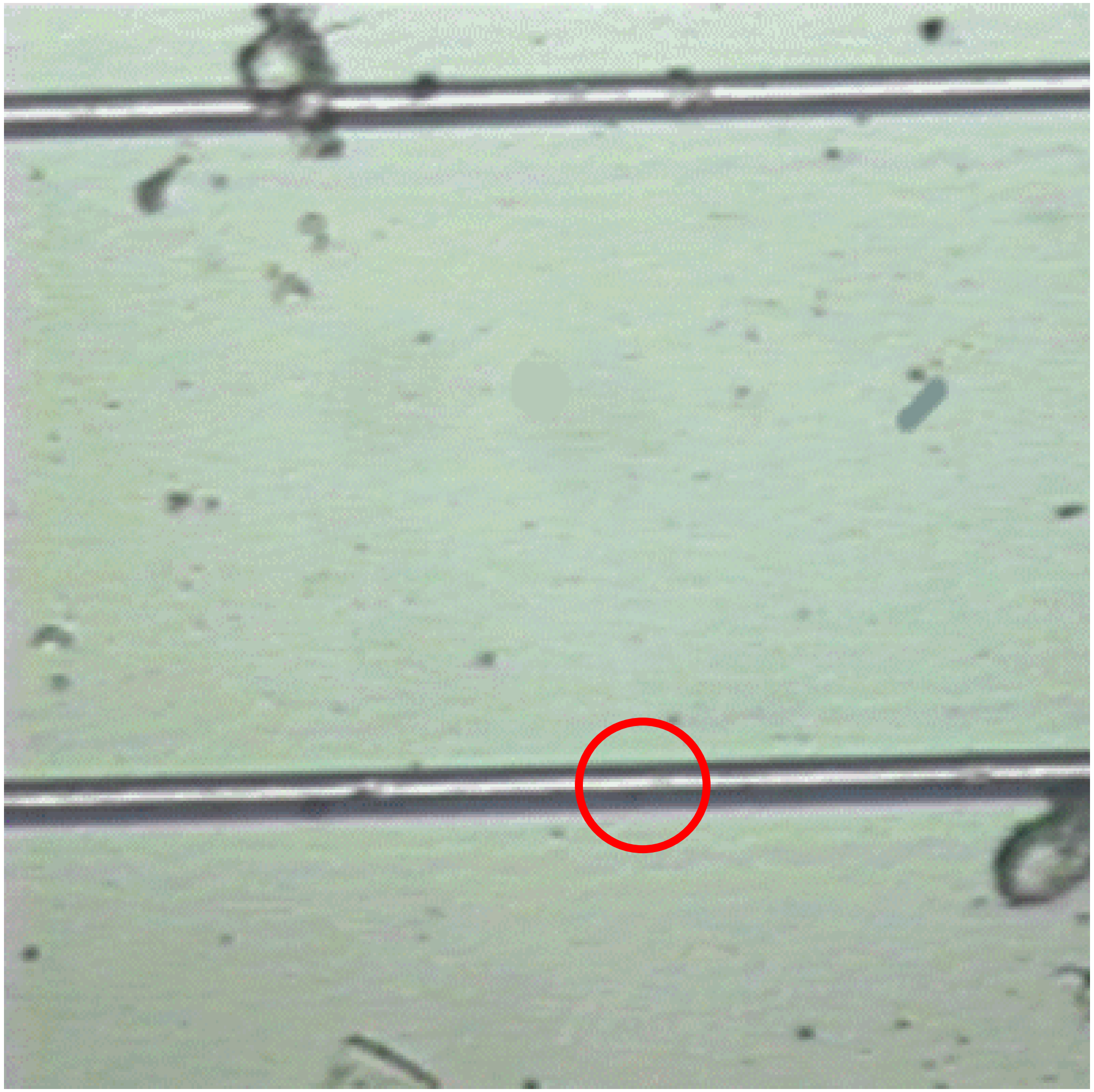


Central portion of the line.



Current density vs. Time to failure of Cu test structures measured at 60C and in air.

Film sequence showing rapid oxidation of Copper Interconnect under a current density of 14.8 x 10^4 mA/cm^2



Discussion of results

One of the most striking findings from this work was the very high exponent (n=3.2) for the current density found for Au conductors, as compared to standard commercial Al:Cu structures. Also, the Au (and Cu) conductors were not able to withstand moderate current densities. The low current densities that caused significant degradation can become a problematic even in normal (rather than accelerated) use conditions. Some of the reasons for these differences when compared to Al:Cu could be:

- The Al:Cu were bamboo structures, where since the line dimensions are of the order of grain sizes, very little grain boundary diffusion occurs. With these structures, Average grain sizes (~ 1 micron) are smaller than conductor dimensions (10 by 4 microns) making grain boundary diffusion an important mechanism which accelerates electromigration (grain boundary diffusion has a lower activation energy than bulk diffusion so electromigration occurs at lower temperatures)
- Al forms a very tough oxide (Al2O3), which is almost lattice matched to the parent metal (Al). This has the effect of passivating the surface, so surface diffusion is very low. Au on the other hand, does not form oxides, so the surface is free to act as an additional diffusion path. This again, has the effect of diminishing the total or "effective" activation energy for electromigration.

Discussion of results (Continued)

•Poor adhesion was found in several of these structures, and delamination of the metallization was often a problem. At elevated temperatures, this could become a problem if delamination occurs in part of the conductor. Since the delaminated area would be dissipating less heat, a thermal gradient could occur and this could accelerate electromigration. During the testing, the increase in resistance with temperature was monitored at very low current densities. The current density was then increase to the test conditions, and the sample resistance was monitored for increases that can be due to Joule heating. This did not seem to be a problem, but if delamination later occurred during the test, then it could explain failure of the metal lines toward the middle portion of the lines, as is seen in the failure analysis. It is also well known that if the current density was too high (causing Joule heating even with good adhesion) the failures would have been observed near the bond pads.

Summary of findings:

•Au test structures can only withstand current densities (***j***) < 9 x 10^5 A/cm^2 (at 200 C). At this value of ***j*** the interconnects failed in less than 15 minutes.

•In Au structures, times to failure vs current density have been used to determine the value of the exponent in Black's equation. $n=3.2$

$$\text{mean time to failure (mttf)} = A\, j^{-n}\, e^{Ea/kT}$$

This exponent is much larger than what was obtained for Al:Cu lines under similar conditions. We attribute this large exponent value to the fact that we do have grain boundary diffusion, surface diffusion, and poor adhesion of the metal lines to the substrates.

•At current densities > 1.8 x 10^5 A/cm^2 recovery is observed in Au interconnects. After a first increase in line resistance, the value of the resistance drops, showing an apparent "recovery".

•Measurements of lifetimes at different current densities in air and at 60ºC show that failure of unprotected Cu lines are mainly due to oxidation failure.