Electromigration Failure in Au and Joule Heating Induced Oxidation in Cu Conductors

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Background/Motivation

Electromigration is the mass transport of a metal due to the momentum transfer between conducting electrons and metal atoms. Electromigration was discovered more than 100 years ago and it has been a problem ever since. As device features reduce in Ultra-large-scale integrated circuits, current densities increase with the metallization layer complexity. These issues make understanding Electromigration (EM) induced failure essential to design more reliable circuits.

In this work, electromigration of copper and gold conductors targeted for micro-inductors in System on a Chip (SoC) application is studied. We intend to use this study to predict:

- Maximum current densities that can be used in micro-inductor interconnects.
- Expected device life-time under use conditions.
- Identify EM failure mechanisms in SoC metallization structures.

Discussion of Results

One of the main findings from this work was the very high exponent (n=3.2) for the current density found for Au conductors, as compared to n=1.7 for 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 (Al_2O_3), 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.

- Poor adhesion was found in several of these structures, and delamination of he 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 increased 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 could only withstand current densities (***j***) < 9 x 10^5A/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 (n) in Black's equation, where meantime to failure (mttf) = $A\ j^{-n}\ e^{Ea/kT}$,where we found that n=3.2

- 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 10^5A/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.