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P-1-7

Investigation of Interconnect Temperature Rise due to Joule Heating and Its Effect on Electromigration Reliability

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1. Introduction

As the miniaturization of ULSI devices proceeds, an operating current density inevitably increases due to the scaling scenario. A number of levels of multilevel interconnections increases steadily to avoid delay of signals also. These circumstances cause an increase in the temperature of ULSI chips due to Joule heating effect. The temperature rise due to Joule heating would affect electromigration (EM) reliability since EM MTF(median time to failure) is in general a function of exp(Ea/kT), where T is an absolute temperature[1-3]. It is apparent that temperature rise is delicately dependent on thermal conductivity of a dielectric film. There is certainly a trade-off between the lowering of operating temperature and the lowering of dielectric constant of insulator films, since an increase in porosity of dielectric film would results in a lowering of dielectric constant and a decrease in the thermal conductivity as well. The aim of the present study is to estimate three dimensional temperature distributions due to Joule heating quantitatively, and further to investigate its effect on electromigration reliability.

2. Methods of interconnect temperature evaluation

We measured temperature distribution of the interconnect structure shown in Fig.1 by an infrared microscopy attached with a high resolution CCD camera (THEMOS-100, Hamamatsu Photonics Corp.) during DC current stressing test at the ambient temperature of 120 °C. The narrowest part of interconnect is 0.5 μm in width, 0.6 μm in height, and 30 μm in length. Since the current density is the highest at this part, temperature rise due to Joule heating is observable at high current density conditions. We carried out three dimensional thermal fluid dynamical finite element (TFDFE) analysis of the same geometry and further investigate various interconnections covered by different dielectric films.

3. Results and discussions

The temperature distributions of Al-alloy interconnect measured by the infrared microscopy are shown in Figs. 2 and 3. It is apparent that the maximum interconnect temperature rose significantly from 140 °C to 300 °C when the current density increased from 12.4 to 23.1 MA/cm^2. There is an nonlinear relationship between the average temperature rise ΔT and the current density J such that $\Delta T = J^n$, where n is 2.1-2.2.

TFDFE analysis agrees well with the observed result in Fig.3 quantitatively when adequate boundary conditions was used; both outside boundaries of Al-alloy interconnection were set to the ambient temperature.

We investigated an effect of dielectric film which overlaid the metal interconnection. Two dielectric films HSQ and porous dielectrics (PD) were chosen for comparison. Thermal conductivity of HSQ is 3.7 mW/cmK, and that of PD is assumed to 0.37 mW/cmK. Both overlayer and underlayer dielectric films were assumed to be the same materials. In the case of unpassivated metal lines, we used HSQ as the underlayer dielectrics. Temperature distributions of the interconnection under DC current stress of 10 MA/cm^2 are shown in Fig.4. Temperature rose more than 150 °C at the middle of the interconnection when PD was used for Al, and it rose about 100 °C for Cu. While it was about 50 °C for Al, and 32 °C for Cu when HSQ was used. Figure 5 shows average temperature rise of interconnection with various dielectric films as a function of current density. Temperature rise is higher in the order of PD/Al, PD/Cu, HSQ/Al, and HSQ/Cu. Thus thermal conductivity of dielectric film is a very important factor that determines net temperature rise. One example of electromigration induced voiding in Al interconnect observed by SEM is shown in Fig.6. The void was formed at the place where line width gradually changed. This suggests that either the atomic flux divergence or the temperature gradient is a key factor to form EM induced voiding.

4. Conclusions

Estimation of temperature rise in a single level interconnection due to Joule heating was performed both experimentally and theoretically. 3-D Finite element analysis well agreed with the experimental results by the choice of boundary conditions. The present results strongly suggest that the use of porous dielectrics significant raise operating temperature and deteriorate electromigration reliability. Thus it is important to establish a guideline of the maximum current density allowed for interconnects with porous dielectrics. For further understandings, thermal conductivity of various dielectrics and 3-D multilevel interconnect structure should be considered.

References

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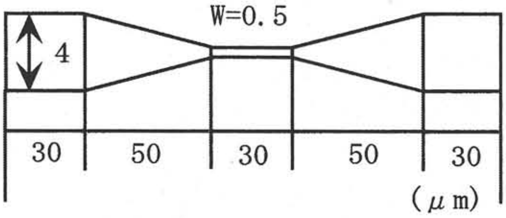

Fig.1 Schematic illustration of a single level interconnection structure used in the present investigation.

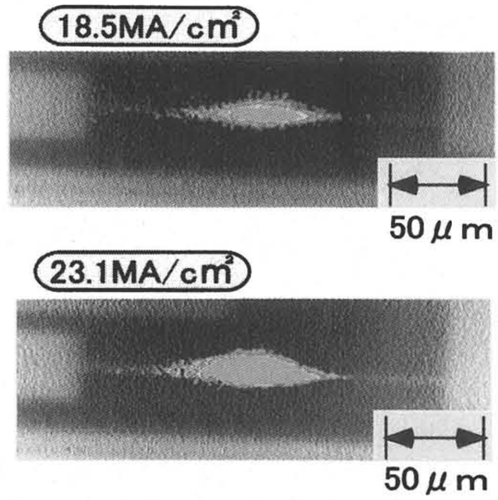

Fig.2 The infrared microscopy images of Al interconnections under a DC current stress. There was no dielectric film on Al.

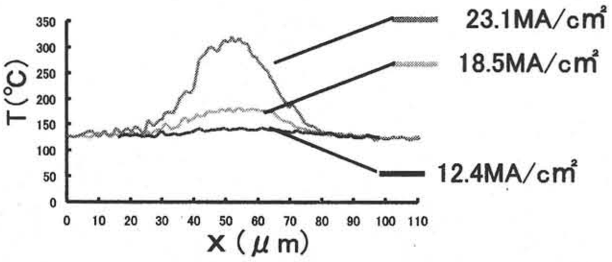

Fig.3 Temperature distribution of Al interconnection measured by the infrared microscopy THEMOS-100 at various current densities. No dielectric film on Al.

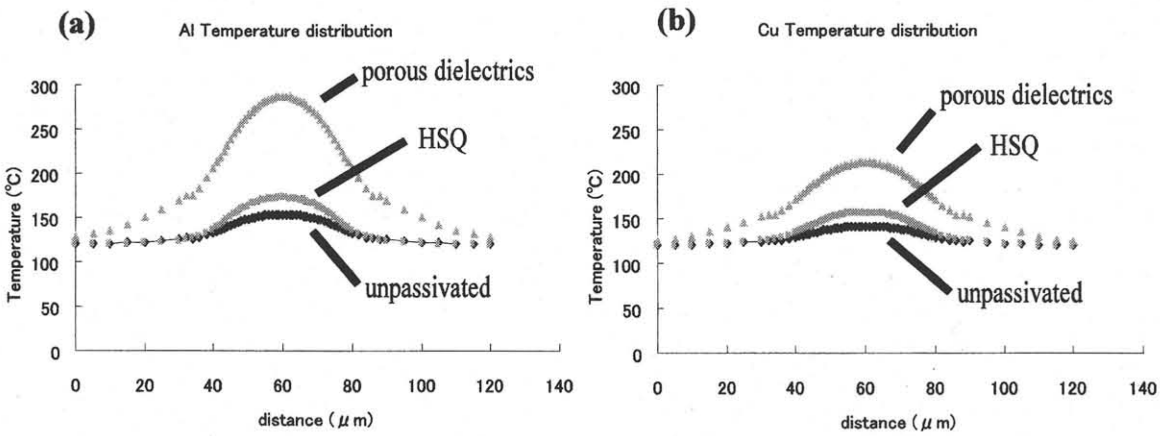

Fig.4 Temperature distribution of the interconection with various dielectric films estimated by a finite element numerical analysis. Current density is 10MA/cm^2, and ambient tempetature is 120 ^{o}C. (a) Al alloy interconnection, (b) Cu interconnection.

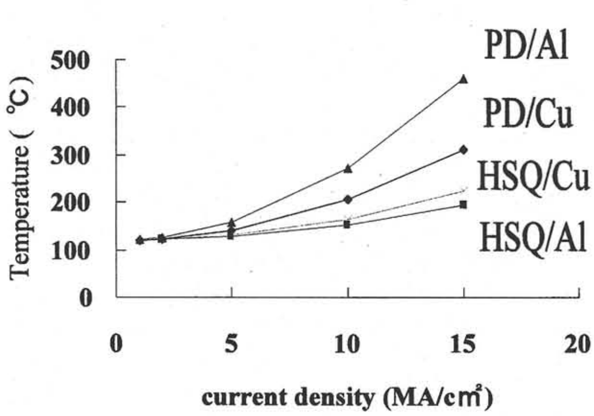

Fig.5 Current density dependence of average interconnect temperature. Ambient tempetature is 120 ^{o}C.

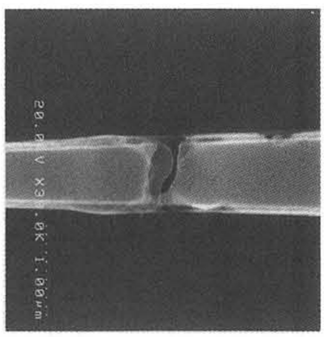

Fig.6 SEM micrograph of the failure site. Disconnection occurred at the place where the gradient of current density existed.