Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 260-261

C-6-3

Off-time Dependence of Pulsed DC Electromigration MTF of Cu Multilevel Interconnection

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1. Introduction

With shrinkage of dimensions of ULSI interconnections, increases in the current density as well as the interconnect layer number impose serious problems on the electromigration (EM) reliabilities [1-2]. There have been many arguments on EM MTF (median time to failure) between DC (direct current) stressed and pulsed DC stressed tests [3], however, only a few studies have been carried out in the high frequency range beyond 10 MHz [4]. The present study focuses on the effect of the pulse off time on the pulsed DC MTF in order to understand the mechanisms of the pulsed EM MTF.

2.Experimental Results

Two levels Cu via chain pattern with 0.42 μm line width is used for EM test. Inter-distance of via holes was 50 μm, and the chain number was 250. We investigated an off-time dependence of the DC pulse EM lifetime. Three stress conditions were used; a simple DC test, a 10 MHz DC test with a duty ratio of 50 % (50 n sec off-time, and 50 n sec on-time), a 6.7 MHz DC test with a duty ratio of 33 % (100 n sec off-time and 50 n sec on-time). The ambient temperature was 300 ^oC, and the current densities for the DC test were 2.5 and 4.5 MA/cm^2. Current densities for the pulsed tests were adjusted to keep the average power constant, so that there was no change in the actual interconnect temperature between different duty ratio tests. In the current stress conditions used, the average temperature increases due to Joule heating were 5.0, and 16 ^oC, for 2.5 and 4.5 MA/cm^2, respectively.

Cumulative failure distributions against time are shown in Fig.1. Lifetime of each interconnection was determined by a 5 % increase in the resistance. There is a clear prolongation of time to failure (TTF) when off-time is increased, and the distribution of TTF is mono-modal. The pulse off-time dependences of EM MTF are shown in Fig.2 for both cases of the current density. MTF increased almost exponentially with the off-time, and it is also shortened by the increase in the current density. The change in MTF due to pulse off-time is rather large compared with that estimated by continuous current model. This means there is some recovery process during pulse off-time.

In order to understand the experimental results, we have investigated one-dimensional (1-D) analysis of build-up of vacancy concentration gradient. In the thermal equilibrium, vacancy concentration C is related to the hydrostatic stress σ by a following equation;

$$C = C_0 \exp(-\sigma\Omega / kT) \quad (1) \quad ,$$

where Ω is an atomic volume, C_0 is a vacancy concentration in the case of no stress, k is the Boltsmann constant and T is absolute temperature. Equation (1) suggests that if we calculate vacancy concentration gradient caused by electromigration, we can estimate a built-up of the stress gradient also. Then we considered the so-called vacancy equation [5];

$$d\,C(x,t) / dt = -\,D \text{ grad } C(x,t) + D\, C(x,t)\, (Z^*eE / kT) \quad (2) \, ,$$

where C(x,t) is a vacancy concentration as a function of x-coordinate and time, D is a diffusion constant ($D = D_0 \exp(-Ea/kT)$) , Z*eE is an electromigration wind force. The first term of the right hand side is a backflow effect caused by vacancy concentration gradient; the second is the electromigration induced drift term. We assumed a uniform current at any x-position. For initial conditions, uniform vacancy concentration of C_0 is assumed. When current pulse is off, the second term of equation (2) is set to be zero, and only backflow due to vacancy concentration gradient exists. One example of the time dependence of vacancy distribution is shown in Fig.3(a). A gradient of vacancy concentration developed with time, finally it reached to a steady state at which vacancy concentration varies almost exponentially with x . This means a linear stress gradient is formed at the steady state as shown in Fig.3(b). We defined MTF as a time when the maximum tensile stress exceeds the critical stress σ_c. Time dependences of the maximum stresses are shown in Fig.4. Off-time dependences of EM MTF thus determined are shown in Fig.5. The results exhibited nearly exponential dependences, and qualitative agreement between experimental results is obtained.

3. Conclusions

Effects of DC pulse off-time on the electromigration life time for Cu interconnections was, for the first time, investigated in a frequency range of a few tens of M Hz. A significant lifetime improvement was observed when the current-off time was increased. The authors proposed theoretical model based on the time dependent one dimensional drift diffusion equation of vacancies to predict the pulsed DC EM MTF, and theoretical estimation qualitatively agreed with the experimental results.

References

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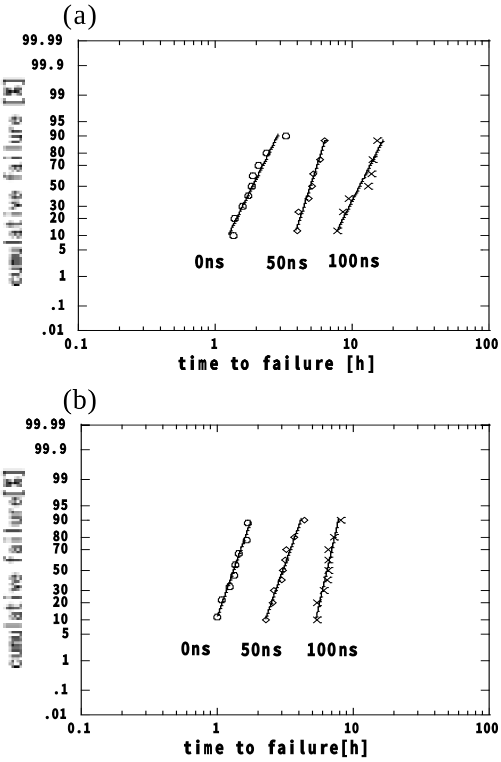

Fig.1 EM time to failure distributions at various pulse off–time conditions. On time is 50 nsec. Temperature : 300 ^{o}C. Current density : (a) 2.5MA/cm^2, (b) 4.5 MA/cm^2.

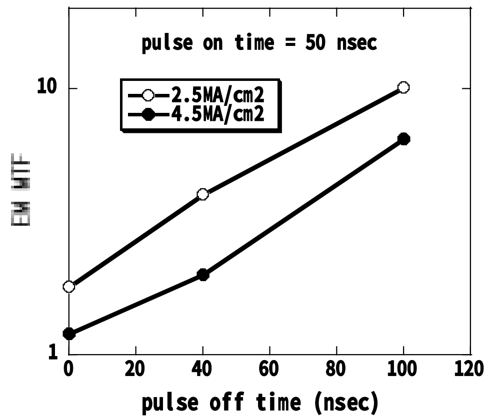

Fig.2 Off-time dependence of EM MTF. 300 ^{o}C, pulse on time = 50 nsec.

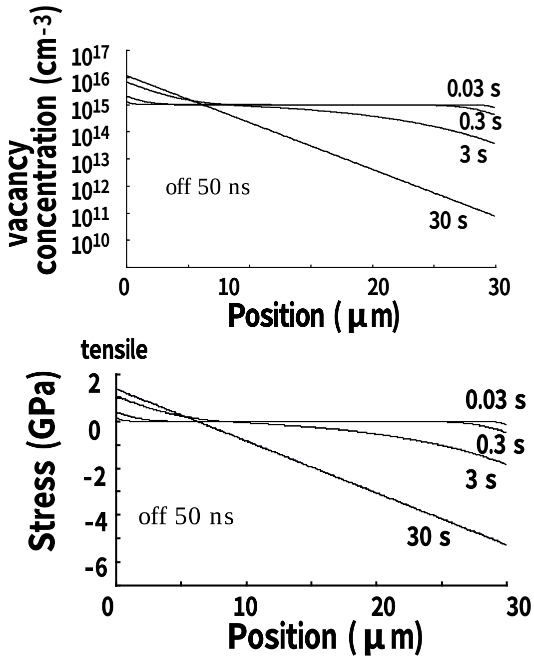

Fig.3. Evolution of (a) vacancy concentration gradient and (b) stress gradient simulated by 1-D vacancy equation in the case of pulse DC stress test.

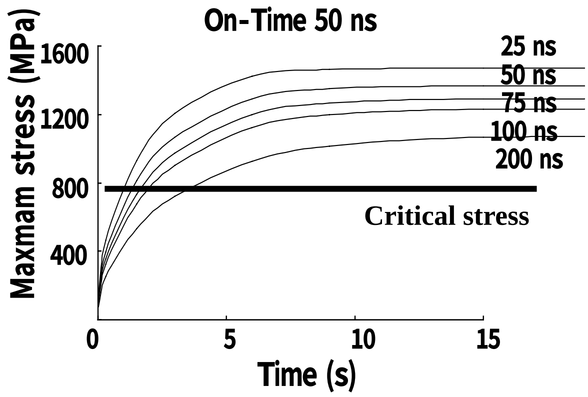

Fig.4 Time dependence of the maximum tensile stress in the 1-D interconnection for various cases of pulse off-time. MTF is determined when the maximum stress exceeds the critical stress.

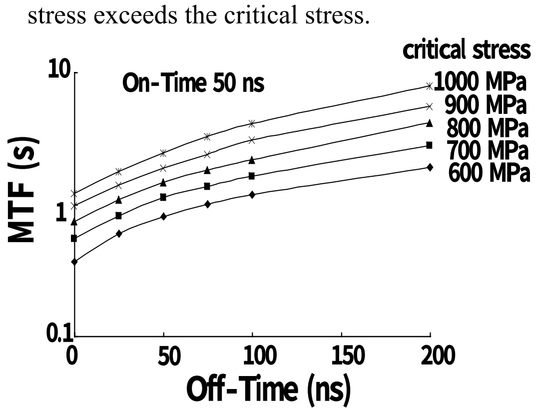

Fig.5 Pulse off-time dependence of EM MTF estimated by 1-D vacancy equation, for various value of the critical stress.