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MICROSTRUCTURAL AND SURFACE EFFECTS ON ELECTROMIGRATION FAILURE MECHANISM IN Cu INTERCONNECTS

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Abstract: It is shown that changes in the microstructure of Cu interconnects lead to qualitative variation in electromigration damage kinetics - from the formation of the open circuit to continuous damage not leading to failure. Surface diffusion acting simultaneously with grain boundary mass transport is shown to be critical for damage formation. Activation energy of electromigration was measured to be 0.95 eV.

INTRODUCTION

Last years Cu is considered to be a possible substitute for Al as a material for interconnects in ULSI circuits. Higher resistance to electromigration (EM) and improved reliability may be expected for Cu since it has a higher activation energy of grain boundary diffusion (1.2 eV against 0.6 eV for Al) which is the main mechanism for EM. However, experiments performed by many authors have shown large variations in the value of activation energy of EM, E_a, - from 0.5 eV to 1.25 eV making questionable the mechanisms for EM in Cu [1].

We supposed that the reason may be variation of EM kinetics which influence the measured values of E_a and that it occurs due to effects of a) microstructure and b) surface diffusion. Variations of some poorly controlled parameters in film preparation, such as composition of the residual atmosphere or contaminations on the substrate, may lead to uncontrollable changes in microstructure (micropores and contaminations in grain boundaries) and influence the processes of void creation and their subsequent growth. Because Cu, unlike Al, does not have a native stable oxide film, the EM process can be complicated by the effect of the surface diffusion, which may also essentially influence the kinetics of damaging by smoothing a film surface [2] and acting as a "healing" mechanism.

In this work we will demonstrate that different microstructures of Cu film result in different kinetics of voids evolution. We connect the latter with the wide dispersion of E_a values.

EXPERIMENT

Cu films of 160 nm thick were deposited in vacuum onto oxidized Si substrates by means of e-beam evaporation. In order to obtain films with different microstructure, we varied some parameters of deposition: substrate temperature, evaporation rate and vacuum. The test structure contained 50 equal, parallel, periodically spaced Cu lines of 2 μm width and of 1 mm length between two contact pads. Accelerated testing was performed by loading a direct electrical current with density of 2×10^6 A/cm^2 in a vacuum 1×10^{-6} Torr at temperatures from 370°C to 410°C.

We used isothermal electrical resistance measurements for determination of E_a of EM mass transfer. The rate of relative electrical resistance change due to EM can be expressed as $(1/R_o)(dR/dt) \sim exp(-E_a/kT)$, where R and R_o are the current and original conductor resistances respectively [3]. In our case R represents the net resistance of 50 parallel connected lines. Testing was carried out using a constant voltage source. Measurements were performed at five temperatures from the range of 370-410°C in a continuous process, without current switching off and vacuum breaking. E_a was determined from the Arrhenius plot of $ln(1/R_o)(dR/dt)$ versus $1/T$.

The microstructure of Cu films before and after EM stressing was investigated by means of scanning and transmission electron microscopy.

RESULTS AND DISCUSSION

It was found that kinetics of EM damage in the Cu films can be very diverse depending on the film microstructure. Figure 1 shows three typical kinds of EM damages which were observed experimentally. The first (Figure 1a) is a void across the conductor line. The second (Figure 1b) is a global thinning of large areas of the conductor line. The third case (Figure 1c) is stripe-voids which propagate along the conductor line and reach a length of tens microns, not leading to an open circuit. It should be emphasized that the three kinds of damages shown on Fig. 1 are extreme cases of EM kinetics, but some intermediated cases are also possible. We presume that observed variety of damages is due to a structural dependent relationship of grain boundary (GB) mass transport with the surface diffusion, when a free film surface serve as a sink for vacancies which arise at GBs in the course of the EM. According to the recent theoretical model of EM [4] which considers coupled GB mass transport and surface diffusion, two different modes of damage formation can exist depending on the grain size. For small grains having large curvature, surface diffusion leads to healing of the damages (grooves) at the GBs and to thinning of the grains, whereas for large grains with small curvature it cannot redistribute material between GBs and grooving results in voids. This model can explain observed damage across the line in the first case (large grains with a mean size of 500 nm, Figure 1a) and thinning of the film in the second case (a mean size of 150 nm, Figure 1b).

To demonstrate the effect of the free surface, we performed comparative experiments on Cu lines and Cu lines covered on their top by a thin Ta layer to prevent surface diffusion. For the uncovered Cu films, notable changes in surface morphology were observed after EM stressing, such as grooving at some GBs and triple junctions (Figure 2a), which we ascribe to action of the free surface as a sink for vacancies. For the Cu films covered by the Ta layer, no surface morphological changes were found (Figure 2b) and voids started only at side walls of the line.

The damages of the third kind (stripe-voids along the conductor line, Figure 1c) have the same nature that thinning has. TEM investigations indicated that these voids arise from lengthwise thinning localized on the width of several grains We think that the latter phenomenon is related to internal (structural) compressive stresses in the Cu films due to fabrication at 300°C with high deposition rates. Such deposition conditions lead to

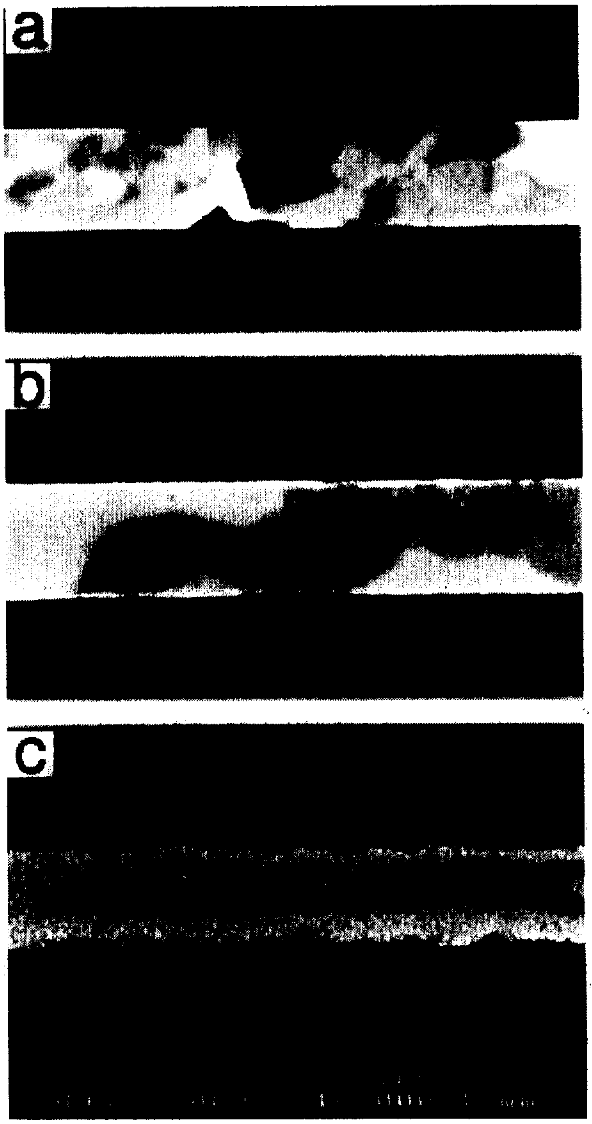

Figure 1. Variety of the EM damage kinetics observed in the Cu conductors fabricated at the different vacuum pressure, substrate temperature, and deposition rate.

(a)- 1×10^{-7} Torr, 20°C, 5 nm/s;
(b)- 5×10^{-6} Torr, 20°C, 5 nm/s;
(c)- 1×10^{-6} Torr, 300°C,50 nm/s.

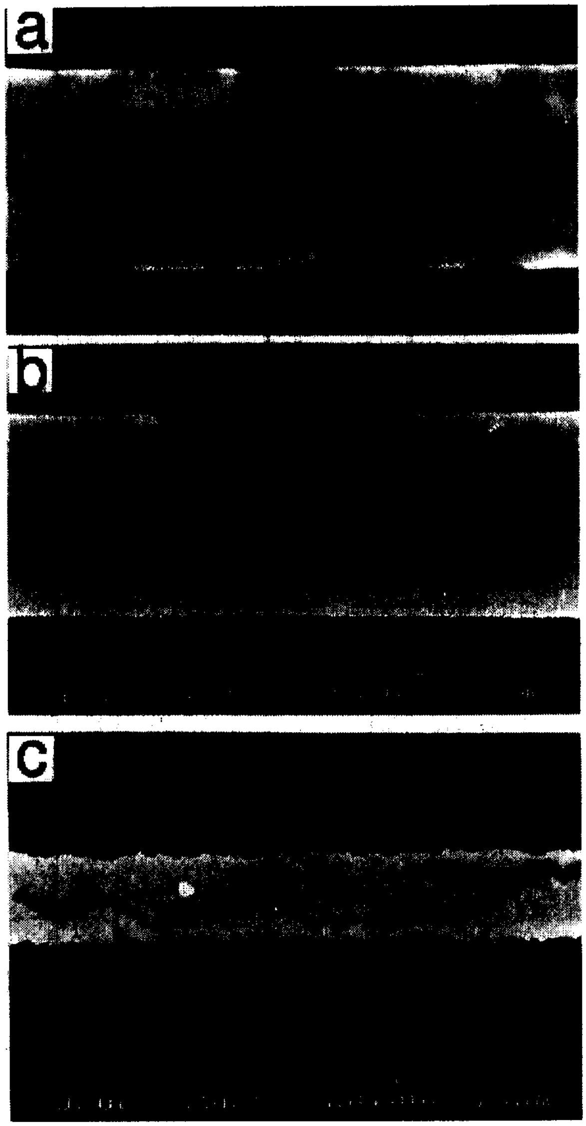

Figure 2. (a),(b)- SEM images of a Cu line and a Cu line covered by Ta after current stressing; (c)- ribbon-like void "locked up" inside the line.

growth of isolated grains which have column shapes and are well bonded to the substrate. They coalesce only in the late stage of the film growth and cause the film to be in tension (to have compressive stresses). These stresses relax at the line borders that lead to a stress gradient across the line and, therefore, to a gradient of vacancy equilibrium concentration. EM mass transport is a vacancy sensitive process and it should be faster inside the line where the vacancy concentration is higher. Some experimental observations of stripe-like voids morphology may serve in favour of such an assumption. Firstly, they arise inside the line, but not at the line borders. Secondly, whenever they grow not exactly parallel to the line axis and start to approach the line side, they do not touch it, but "push off" from it changing their direction (Figure 2c).

The rate of electrical resistance change at early stage of EM is thermally activated process [3] and it was used for determination of E_a of EM mass transfer. For these measurements, we used a sample with the EM kinetics of the second type (thinning, Figure 1b). In this case of a small grain size, the surface diffusion is fast enough to redistribute material on the film surface between the GBs, and the observed electrical resistance change is determined only by mass removal and independent of details in void growth process. The value of the E_a was found to be 0.95 eV (Figure 3), that is close to the value of E_a for GB diffusion, indicating that GB diffusion is the limiting mechanism of EM mass transport.

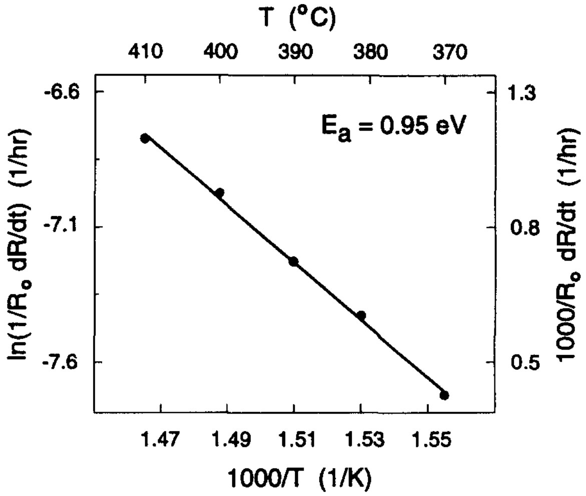

Figure 3. Arrhenius plot of the rate of resistance change for the Cu test structure.

In summary, we demonstrated that different microstructures in Cu films results in large diversity of kinetic processes of EM mass transfer. In some extreme cases the voids in form of long narrow stripes along the Cu line were observed. Such type of EM damages has never been reported in Cu or any other material. Within framework of the existing theoretical models our findings suggest that surface diffusion plays an essential role in EM kinetics.

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