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Real-Time TEM Studies of Electromigration in Submicron Aluminum Runners

S. P. RIEGE, A. W. HUNT, AND J. A. PRYBYLA
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
908-582-5053; Fax: 908-582-2300

Electromigration dynamics in deep-submicron Al interconnects has been directly observed in *real-time* using in-situ transmission electron microscopy (TEM) techniques. We use advanced submicron Al(0.5wt%Cu) runners and a novel sample design which dramatically minimizes Joule-heating, while allowing many runners to be stressed at once and observed inside the TEM. The composition, thickness, and widths of the Al interconnects were chosen to coincide with that currently or soon-to-be used in actual manufactured devices. The time-evolution of the EM-induced processes were captured and recorded in real-time on video-tape, as well as with conventional micrographs. By these methods, the dynamics of EM phenomena is seen with striking clarity and detail. We can observe voids form, grow, migrate, pin, fail a runner, and heal all with respect to the detailed local microstructure of the runners.

A main reliability concern in high-density Si VLSI technology is the many meters of metal interconnect needed to build a single integrated circuit. Owing to electromigration (EM), this concern increases with the level of integration. At present, the phenomenon of electromigration (EM) is not understood well enough to be able to predict EM behavior of interconnects under use conditions. Therefore, a primary motivation of the present work is to advance our understanding of electromigration micromechanisms toward enabling the development of realistic predictive models of interconnect reliability.

The experiments were carried out in a JEOL 2000FX transmission electron microscope. A special specimen holder was used which allowed TEM observations to be recorded while simultaneously heating and passing electrical current through the sample. We used the standard current density for accelerated testing of $2 * 10^6 A/cm^2$, and performed the experiments for a variety of temperatures ranging from 200 to 370°C. The experiments were done using constant *voltage* testing. The samples consisted of 4000 Å thick Al(0.5wt%Cu) patterned over a TEM-transparent window into five runners in parallel, with linewidths 0.2, 0.3, 0.5, 0.8, and 1.0 μm. Large Al heat sinks were patterned on both sides of each runner on the TEM-transparent window, which dramatically minimized the Joule-heating to <25C. Both passivated and unpassivated samples were examined. A schematic of the sample structure is shown in Fig. 1. Video recording of dynamic processes was done using a Gatan image intensifier camera and a video cassette recorder (VCR).

Systematic studies have been performed on the dynamics of EM as a function of linewidth, passivation state, and temperature in the range of 200 - 370 C. We have enumerated each of the various void formation, growth/migration, and failure mechanisms observed and describe the strong relationship between the processes. Also hillocks and hillock dynamics have been documented, and we we have examined in detail for the first time, healing dynamics of open-circuit failed runners. In this paper, we will focus on void migration and failure dynamics.

Even at the mildest stress conditions studied (current density = $2 \times 10^6 A/cm^2$, and temperature = 200 C) where runners take many weeks to fail, we find that voids form within an hour of testing. This demonstrates that the rate-limiting step for the failure process is not void formation but void *growth*. This result is an important ingredient in the development of realistic EM models. We observe a large variablity in void dynamics and time-to-fail (TTF) of runners even when they have nominally the same microstructure and linewidth. Documenting and understanding this variability is also critical for developing predictive models.

In Fig. 2 we show an example of one of the most common growth/migration processes observed, the "inch-worming" migration mechanism. A triangular-shaped void is observed at the sidewall and intersecting a grain boundary (Fig. 2a). It then transforms into a long and narrow void along the sidewall (Fig.2b,c) and upon doing so begins to migrate rapidly, which is what we refer to as "inch-worming". The void passes through the first two grain boundaries (B1 and B2) without much perturbation, but its motion is greatly perturbed upon encountering grain boundary B3. It gathers up at this grain boundary as shown in Fig. 2d and 2e, and remains pinned this way for some time. The chain of events described here is very typical for this mechanism. Other migration mechanisms will also be described including growth/migration via thinned-out regions along the z-direction in plan-view TEM.

It is found that the failure dynamics is closely related to the growth/migration dynamics. Fig. 3 shows the time-evolution of an open-circuit failure by the "inch-worming" migration mechanism. A void had been inch-worming along the sidewall but was halted upon encountering a grain boundary B1 shown in Fig. 3a. The void began to pile up at this boundary and also within the grain momentarily as shown, which is unusual. The part of the void which had gathered within the grain subsequently moved quickly over to the grain boundary B1 as well (Fig. 3b) and the gathering up at B1 then proceeded until complete open-circuit failure resulted (Fig. 3c,d). The shape of this failure site is a hallmark of this mechanism (open-circuit with a long tail downwind). Other failure mechanisms will also be described including failure by the thinned-region growth/migration mechanism, and failure by two-void mergers.

Finally, we will describe the major differences observed in the frequency with which a particular mechanism (of growth, migration, failure, etc.) occurs as a function of linewidth, temperature, and passivation state. There are also major differences in the time-scale at which the observed mechanisms proceed which depend on these things.

This work demonstrates the complexities of EM-induced processes in submicron Al runners and the necessity for using real-time methods to understand them. By our in-situ TEM method, we directly observe that the microstructure has a very strong influence on void and failure dynamics. Nearly all failures are found to occur along grain boundaries. We also directly observe the important role of the Al/passivation interface and the *free* Al surface (formed upon void nucleation) on electromigration in submicron Al runners. Realistic modeling of EM will have to include prediction of the large variety of proceeses reported herein.

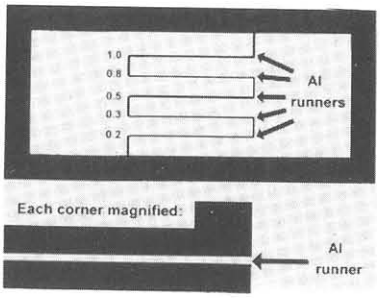
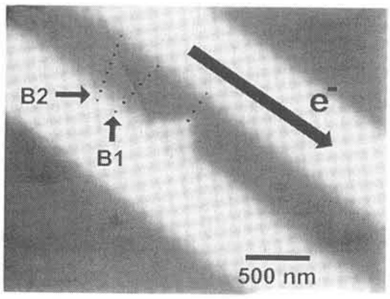


Fig. 1. Schematic of sample.
Black = no Al; White = Al



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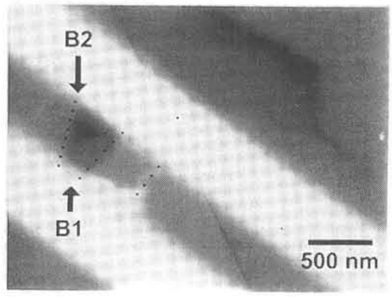

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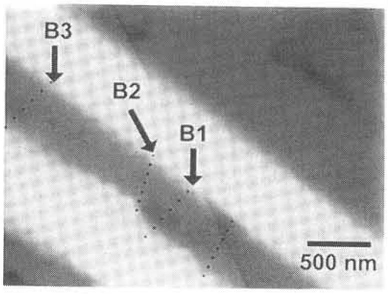

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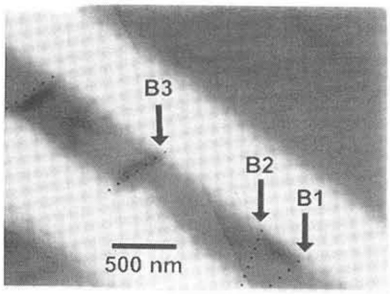

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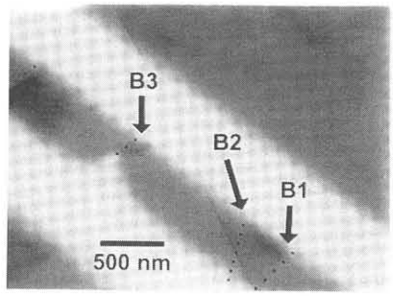
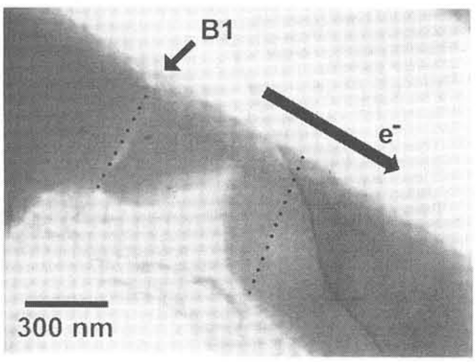
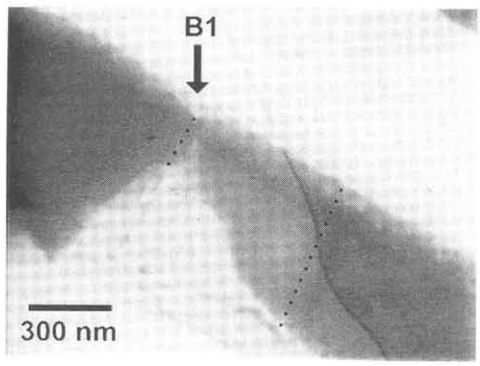


2 (e)

Fig. 2. Time-series showing "inch-worming" migration process.



3 (a)



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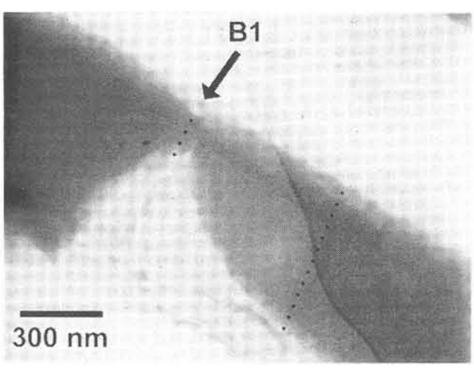

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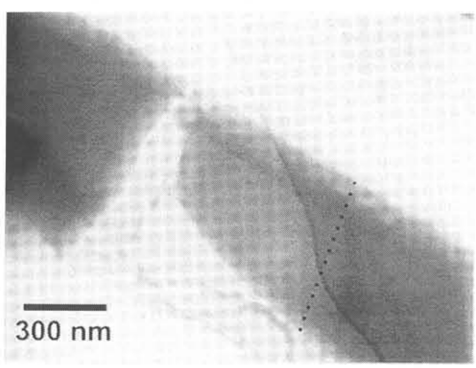

3 (d)

Fig. 3. Time-series showing interconnect failure through the "inch-worming" migration process.