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Void nucleation on intentionally added defects in Al interconnects

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Void nucleation in passivated aluminum interconnects was studied using high voltage scanning electron microscopy. To test theories about stress-induced and electromigration void nucleation, Ar ions were implanted into Al specimens. The Ar atoms precipitated and formed bubbles that served as nucleation sites with high surface energy. In the implanted samples, voids formed away from the interconnect sidewalls, in contrast to voids in ordinary passivated Al interconnects. The evolution of the void volume was also affected by the reduction in the nucleation barrier. These results strongly support the theory of void nucleation on interface flaws in Al interconnects. © *1999 American Institute of Physics.* [S0003-6951(99)02031-8]

The development of a predictive model of electromigration failure is an important goal in research on interconnects. Fundamentals of the electromigration failure process have been discussed elsewhere.[1] Most models of electromigration focus on the evolution of stresses or the accumulation of vacancies in an interconnect.[2,3] Failure is taken to be the accumulation of a certain vacancy concentration or a critical amount of tensile stress. Recently, the details of the nucleation process have been examined. It is hypothesized that void nucleation is impossible on any realistic time scale, unless voids form on pre-existing defects.[4] We have tested this theory by selectively introducing nucleation sites into aluminum interconnects.

Voids in passivated lines nucleate exclusively on the interface between the passivation and the line sidewall. We have tested ~100 metal lines in recent research programs; in every experiment, all of the voids first appeared at the edge of the line. This has also been observed in other studies.[5] While it may not be surprising that voids nucleate on the line sidewalls, it might be surprising indeed that they do so there exclusively. It has been hypothesized that defects with a high enough surface energy to serve as void nucleation sites exist only on the line sidewalls.

Electromigration voids typically nucleate at the cathode end of a polygranular segment where a grain boundary intersects the line sidewall.[6–8] This configuration is apparently a necessary, but not sufficient, condition for void formation. There are many more potential nucleation sites than voids formed in an electromigration test. There must be a feature that distinguishes the sites at which voids nucleate. In some *in situ* experiments, many voids formed at the same spot.[9] One void would nucleate, grow, and then move away. After the first void migrated, a new void would form at the original site and then the process would repeat. This phenomenon suggests that there was something unique about that area of the line. A likely explanation is that a defect existed at that point, which served as a nucleation site.

Dry etching of the aluminum lines is a probable source of these defects. Interconnects are processed to have vertical sidewalls. This is typically accomplished by coating the newly formed sidewalls with a combination of sputtered mask material and other chemicals in the chamber.[10] By controlling the amount of this material that is deposited onto the sidewalls, one can achieve a vertical profile. The removal of this layer after the etching process is very important. If a small amount of this material remains after the cleaning step, it could serve as a site for void nucleation. The postetch cleaning process has a large effect on interconnect reliability.[11,12]

In early descriptions and models of the electromigration failure process, void nucleation was largely overlooked.[13] At the time, this was probably a justifiable assumption. Judging from early images of electromigration damage, there were many voids from the onset of the test.[14] However, as the quality of integrated-circuit (IC) processing increased, the void incubation time increased as well. Currently, the time to void nucleation can be a very large fraction of the entire lifetime of a line.[15,16] It is now important to consider the barrier to void nucleation in any model of electromigration failure.

Nix and Arzt showed that homogeneous void nucleation in the bulk of a line was unlikely.[17] Flinn demonstrated that barrier-less void formation was theoretically possible, if voids formed on pre-existing free surface.[18] Gleixner *et al.* calculated nucleation rates for void formation in the bulk of a line, on the line sidewall, on a grain boundary, in an interface notch, and on an interface flaw.[4] They found that nucleation rates were orders of magnitude too low for any case except that of nucleation on an interface flaw. Clemens *et al.* extended the treatment of Flinn to allow a void to grow off the defect.[19] They found that this could lower the nucleation barrier further. All of these theories suggest that void formation, even under extreme amounts of hydrostatic stress, is not possible unless voids nucleate on a pre-existing defect. The nucleation barrier in any other case is simply too high.

We tested these theories by selectively introducing void nucleation sites into a line. Bubbles of noble gas atoms proved to be an ideal defect for this project. Noble gas atoms

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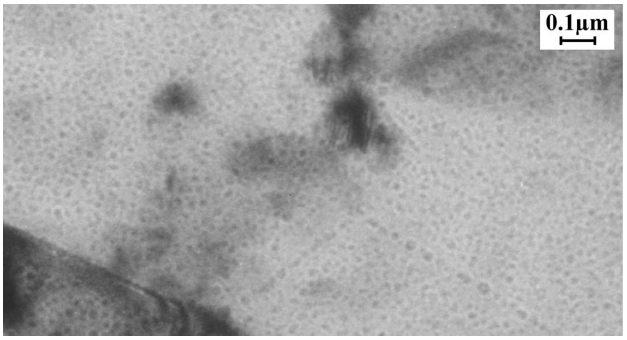

FIG. 1. A TEM micrograph of Ar bubbles in an Al thin film.

are essentially insoluble in metals. After ion implantation, these atoms precipitate and form small bubbles.[20,21] Aluminum will not bond to the noble gas atoms. Thus, the surface energy of the bubbles is essentially that of a free aluminum surface and suitable to serve as a nucleation site.

We employed transmission electron microscopy (TEM) to determine the precise dose of argon ions to implant into the aluminum samples. Using previous work[22] as a starting point, 10 wafers (50 nm SiO_2/5 nm Ti/700 nm Al/10 nm Ti/50 nm SiO_2/Si) were implanted with 200 keV argon ions at doses from 10^{15} to 10^{17} ions/cm^2. Plan-view TEM specimens were made from each wafer. Images from each specimen were digitally analyzed and the distributions of bubble sizes were measured as a function of ion dose. One such image is shown in Fig. 1. An argon dose of 1.56×10^{16} ions/cm^2 produced a median radius of 5 nm. This radius was chosen, because the stress level for void nucleation on a defect that size was slightly above the amount of thermal stress in the line.

A stack of 5 nm Ti on 514 nm Al on 50 nm of SiO_2 on a Si wafer was prepared with standard, integrated-circuit, fabrication techniques. The wafers were patterned and etched to form test structures. The specimens were then encapsulated in 50 nm of silicon dioxide to protect the surface of the lines during ion implantation. A hard photoresist mask blocked the ions from selected areas and structures. In this manner, unimplanted control specimens were fabricated on the same wafers as the implanted specimens. The unmasked areas on the aluminum lines were then implanted with 200 keV argon ions at a dose of 1.56×10^{16} ions/cm^2. After the implantation, the photoresist was stripped. An additional 950 nm of silicon dioxide was deposited on the wafer, and the bond pads were exposed.

We employ a backscattered electron imaging technique. High-energy electrons (120 keV) penetrate through a thick dielectric layer, elastically scatter from within the metal interconnect line, and then re-emerge from the sample surface. The electron beam scans across the sample and the magnitude of the backscattered electron current from every point forms an image. The development of this instrument to perform *in situ* testing has been documented elsewhere.[23]

Thermal stress-induced void nucleation occurs by the same process as electromigration void nucleation. Given a high-enough hydrostatic tensile stress and an appropriate site, a void will nucleate to release the strain energy in the line. Stress-induced voids also form exclusively at the line–passivation interface. (One exception to this rule is lines under a silicon nitride passivation. It is thought, in this case, that hydrogen in the silicon nitride diffuses into the metal and embrittles it.[24,25])

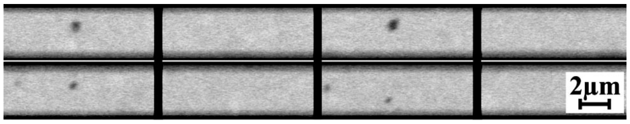

FIG. 2. An 80 μm segment of an 300-μm-long aluminum line. The second 40 μm are stacked under the first 40 μm. The three, black, vertical lines divide the image into 10 μm segments. The first, third, fifth, and seventh segments have been implanted and have voided.

There were no stress-induced voids in the unimplanted, control structures. In the areas of the samples that had been implanted, stress-induced voids were present. Most voids formed away from the sidewalls of the line. A particularly good example of this was in a structure in which every other 10 μm segment was implanted with argon. In 14 of 15 segments that were implanted, stress-induced voids were present. In each of the 15 unimplanted segments, there were no stress-induced voids. An 80 μm segment of this structure is shown in Fig. 2. In this figure, at least one void can be seen in each implanted segment, and these voids are located near the middle of the line. In a few cases (not shown), the stress-induced voids were located on the sidewalls.

This experiment demonstrates that there is sufficient driving force for void nucleation in the interior of the lines, as one would expect. Stress-induced voiding is suppressed in the unimplanted areas by the lack of nucleation sites. Given a large enough site, voids will form. (The median bubble radius was chosen to be smaller than the size necessary to nucleate stress-induced voids; however, the bubbles on the upper end of the size distribution were indeed large enough to form voids at these stress levels.)

Electromigration tests were conducted on these samples at 212 °C and 30 mA/μm^2. In these tests, voids formed readily, both in the interior of the line and along the line sidewall. An electromigration void that nucleated in the bulk of a line is shown in Fig. 3. This is significant, as it shows that the driving force for void nucleation in the interior of a line is sufficient to nucleate a void. The reason why voids do not form there is that there are ordinarily no nucleation sites away from the sides of the line. The fact that some electromigration voids still nucleated on the line sidewalls is not surprising given that the largest flux divergences probably existed there. Voids formed in unimplanted specimens exclusively at the line sidewalls, as defects suitable for void nucleation were located solely there. Given an appropriate nucleation site, voids formed away from the line sidewall.

Introducing nucleation sites increased the total amount of void volume as a function of time. The void volume of three lines that were implanted and one that was not im-

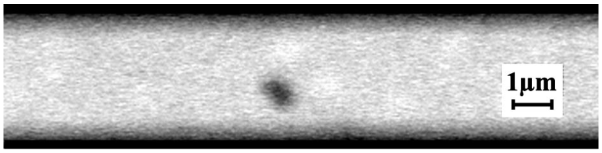

FIG. 3. An electromigration void that nucleated in the bulk of the line. This image was taken 1.3 h into the test.

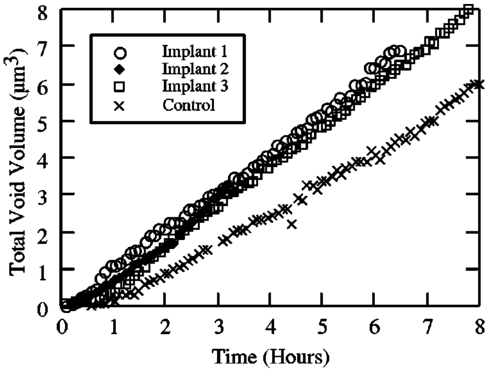

FIG. 4. Total void volume vs time. Data from the unimplanted control specimen are denoted with *X*'s. The evolution of the void volume is slower in the control specimen.

planted (all from the same die on the same wafer) are plotted in Fig. 4. The evolution of the void volume was very similar in each of the implanted specimens and was markedly slower in the unimplanted sample. Faster, more repeatable total damage is precisely the behavior one would expect from lowering the nucleation barrier.

If the nucleation barrier was lowered or removed, the total number of voids in a line should very quickly reach its maximum. (There might be a few exceptions to this prediction, e.g., a void moving away from a site of flux divergence and a new void forming at that same site.) This behavior was observed in the implanted specimens. Nearly every void that formed in a line, formed almost immediately after the start of the test.

In conclusion, stress-induced voids were present in areas of specimens that had been implanted. Generally, these voids formed away from the sidewalls. This is in contrast to ordinary lines, in which stress-induced voids form exclusively on the sidewalls. Some electromigration voids nucleated away from the sidewall. This behavior is again in contrast to what is normally seen in passivated aluminum interconnects. The evolution of the void volume with time was very similar from implanted line to implanted line and in general faster than in the nonimplanted lines. The total number of voids in a line saturated quickly in the implanted samples. All of these observations lend strong support to the theories of heterogeneous void nucleation exclusively on pre-existing defects. In conventional Al interconnects, the line sidewalls are the surface most exposed to damage. Because the upper surface of damascene copper interconnects are likely to be the ''dirtiest,'' it is likely that voids will form at that interface in these newer metallizations. Careful cleaning of the interfaces of interconnects is a key method to improve reliability.

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