Computer Failures: A Nonproblem?

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It is common knowledge that machines with moving parts eventually break down or wear out due to friction, fatigue, or other mechanical failure mechanisms. How about computer chips? Are there also moving parts? Well, not like those found in engines, motors, and generators. Still, electrons move with high velocity in transistors, for example, and particularly in the metal stripes which interconnect them. Consequently, computer chips may eventually fail by a mechanism which is called electromigration. Specifically, electromigration is the forced motion of (metal) ions under the influence of an electric field. It is potentially one of the most pernicious failure modes in interconnects of large-scale integrated microelectronic devices. The momentum exchange between the electrons and the metal ions causes the ions at normal operating conditions (under 200°C) to migrate predominantly via grain boundaries. This eventually leads to voids and extrusions near grain boundary triple points and finally to failure of an entire device.

Electromigration in thin films has been on the agendas of numerous scientific and technical meetings for about 30 years. In fact, several topical conferences and symposia have been exclusively dedicated to this phenomenon. The ensuing discussions usually dealt with one of the most researched failure mechanisms which occur in computer chips. Yet, representatives of many leading electronic companies have publicly claimed that they have never seen a microcircuit which has failed "in the field" due to electromigration involving chips from their own respective companies. Despite this claim, the countdown of at least one space mission, originating from Cape Canaveral, was interrupted some years ago because of an onboard computer failure. This occurrence was unmistakably traced back to a failure in thin metallic connection stripes of a microcircuit, costing the U.S. taxpayer $1.5 million for removing the fuel from the rockets and subsequent refueling. Moreover, some of the bipolar logic parts used around 1980 in space shuttle computer systems failed because of electromigration. (The more problematic failures occurred in September 1981 after about 20,000 operating hours at about 90°C junction temperature and 2×10^5 A cm^{-2} current density and were caused by electromigration-induced aluminum extrusions through the protective overcoat.) Each microelectronic company of repute employs a permanent staff of scientists and engineers who monitor the electromigration-related failures and investigate new (and old) avenues which are intended to alleviate this persistent "nonproblem." Indeed, failure rates are actually "normalized." One defines one failure in 10^9 device hours (number of devices multiplied by operating hours) to be one FIT. As an example, for most consumer products manufacturers strive for about 20–50 FITs over about 100,000 hours of operation. One has to keep in mind, however, that failures in microelectronic devices are of statistical nature. This means that one computer chip may fail just one day beyond the warranty period whereas others give up several years later.

Can something be done about this? In principle, yes. Electromigration is essentially a *materials problem.* Materials need to be employed for these interconnects which have an extremely high resistance to electromigration (concomitant with a good electrical conductivity). Some of these possible materials are already known today but are not used yet for good (or not so good) reasons. For example, tungsten is much less susceptible to electromigration than the commonly used aluminum which contains additions of a few percent copper and sometimes 1% silicon. However, tungsten has a room-temperature electrical resistivity which is about twice as large as for pure aluminum. A high resistance in turn promotes Joule heating. This heat needs to be removed from the chip, which is not so easy since the thermal conductivity of silicon, and particularly of SiO_2, is relatively low compared with that of metals.

As a second alternative, one could use gold, which has somewhat better conductivity than aluminum and *substantially* better resistance against electromigration. Nevertheless, the electronics industry is at present reluctant to replace aluminum metallizations for silicon devices by gold because of cost (!), a lack of suitable processing procedures, and particularly because gold, once it has diffused into silicon, may cause deep-lying recombination centers for the current carriers. A barrier layer between gold and silicon has to be inserted, therefore, which also improves the adhesion of the gold on the substrate. Barrier layers are, incidentally, widely used, even in the case of Al metallizations, and should therefore not deter the usage of gold.

A third alternative for replacing aluminum is pure copper, which shares with gold good conductivity and acceptable electromigration resistance. However, copper may also introduce carrier recombination centers in silicon unless a barrier layer is inserted between the two materials. Additionally, copper causes processing and corrosion problems which are not yet completely under control.

Fourth, experiments have shown that aluminum can be continued to be used if different deposition methods are applied. One of these processing procedures is a technique in which some of the aluminum atoms are ionized by electron bombardment while they are still in the vapor state. The aluminum ions are then accelerated by an electric field toward the substrate on which they are deposited. Substantial improvements in electromigration resistance (one order of magnitude compared to Al) have been achieved with this "self-ion enhanced physical vapor deposition" technique which, incidentally, also improves the filling of narrow and "deep" via holes with metal.

Some techniques to improve electromigration resistance are essentially known. However, the implementation of these techniques requires substantial financial investments which industry is reluctant to provide so long as there are no compelling reasons to do so. Indeed, it is argued that an average computer may become obsolete long before electromigration-induced failures require a replacement of the device. Moreover, it is often stated that failures yield a "repetitive market" which in turn creates jobs and profitable returns on investments.

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