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Failure times in metal lines

The increase of density of transistors on integrated circuits increases the concern about the reliability of the chips and, in particular, of the metal wires that connect the circuits. Metal lines sometime fail due to migration of metal atoms under the influence of electric current and elevated temperatures. Experiments show that under very high stress, failure times are almost always approximately lognormally distributed. This usually forms the basis for extrapolating failure times from high stress conditions to normal operating conditions, but it is not really known whether the extrapolation is accurate.

On March 17, 1995 Leonard Borucki from Motorola Advanced Custom Technologies described several theories that have been advanced to explain the universally observed failure distribution. He also explored the question whether the observed failure pattern offers any clues about the nature of the underlying transport processes that lead to failure.

13.1 Electromigration

Aluminum lines used to connect transistors in the chips are produced by micro-electronic technology: First one deposits aluminum atoms over the chip to form a thin film of crystals (this process is called epitaxy) and then one radiates the surface (through mask) and etches out much of the aluminum film so that what is left is a series of aluminum wires. Figure 13.1 shows a typical wire.

Current in an aluminum line causes slow transport of aluminum atoms along the grain boundaries: Aluminum atoms reach once in a while a sufficiently high energy level which make them hop and exchange position with vacancies; this phenomenon is called electromigration. Thus aluminum is depleted in some regions, resulting in thinning and voiding, as it accumulates in other regions, forming hillocks; see Figure 13.2. Grains and surfaces can provide sources and sinks for vacancies. Passivation (i.e., layers which are deposited to protect the chip) and alloying help reduce or eliminate sources of vacancies and suppress hillock formation.

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Figure 13.3 shows experimental results of time to failure. The horizontal axis gives the percentage of lines that failed, on the normal distribution scale. The vertical axis measures the time (in hours) to failure, on the logarithmic scale. The four experiments are for current densities of 1, 2, 3 and 4 MA/cm². (The time to failure decreases as the current density increases.) The fact that the experimental points for each current density lie approximately on a straight line means that the time to failure $t_f$ has lognormal distribution. For more information on experimental results see [1] and the references therein.

13.2 A mathematical model

Kircheim and Kaeber [1] have developed a theory to explain the lognormal distribution of $t_f$. To each 10 grain boundaries of equal length, they