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I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

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"Metal Lines Failure in Microelectronic Devices"

D. Nobili
L.A.M.E.L. - CNR
via dei Castagnoli 1
40126 Bologna
Italy

These are preliminary lecture notes, intended only for distribution to participants.

METAL LINES FAILURE IN MICROELECTRONIC DEVICES

D.Nobili, A.Scorzoni.

CNR-LAMEL. BOLOGNA

This lecture aims to provide an introductory and very simplified picture of the phenomena which lead to failure of the metal lines used as interconnects in microelectronic circuits. High electric current densities lead to a flow of the constituents atoms accompanying the current of electrons. **Electromigration (EM) is considered an important reliability concern** in the electronic device industry as the atomic fluxes induced by the electron current can give rise to the formation of voids and open circuits, or to hillock formation and short circuits between nearby interconnects. The problem is exacerbated because of the trend of increasing the density of devices in Large Scale Integration (1).

Diffusion towards the positive electrode has been extensively observed in metal lines. The theoretical basis of this phenomenon can be found in the papers by Huntington and Grone (2) and Bosvieux and Friedel (3) which provide an expression for the 'friction force' exerted by the 'electron wind' on the atoms.

The atom flux J due to EM is most frequently related to the electron current density I through the phenomenological equation:

$$J = (N Z q \rho I / K T) D_0 \exp(- E / K T)$$

where N is the mobile element atomic density, Z its effective charge number, q the electronic charge module, ρ the electrical resistivity, E and D_0 the activation energy and the preexponential factor for the diffusion. The product $Z q \rho I$, which is the driving force acting on the metal ion, can be quite consistent, e.g. in Aluminium at room temperature about 30 eV / m for $I = 10^4$ A / cm^2.

In the absence of divergence of the atomic flux EM cannot induce failures in

the metallic conductor: as much material would reach any section as the material which leaves the section itself.

Non uniform grain structure has been recognized as the most important factor for divergence of the atomic flux. Due to the high value of the grain boundary diffusivity with respect to the diffusivity in the bulk, a mass build up can occur at the boundaries between small and large grains, whereas a corresponding mass depletion takes place at the boundary from large to small grains. Hence a uniform grain size is desirable to reduce EM damage. **The increase in average grain size with respect to linewidth has been shown to be particularly beneficial in improoving the reliability of the metallic films as demonstrated in bamboo structures, with grain boundaries perpendicular to the current flow**. The improovement is in addition due to the increase in the activation energy for the diffusion resulting from the larger bulk contribution.

Another factor leading to appreciable flux divergence are the temperature gradients, as they can produce gradients in the diffusion coefficient.

Since the mass tranport in close packed metals takes place by vacancy diffusion, vacancy supersaturation occurs in the regions where the atomic transport results in mass depletion.

Nucleation sites for the formation of voids by vacancy 'precipitation' are provided by structural inhomogeneities, mainly grain boundaries and impurity clusters. In particular cavities formed by grain boundary sliding (a typical creep mechanism) can promote vacancy aggregation even at low supersaturation. **The migration and coalescence of voids can lead to their rapid growth**. In the absence of trapping a void of radius R can migrate due to surface diffusion with a velocity inversely proportional to R . The smaller voids then move faster and catch up with the larger ones leadind to rapid coalescence and line failure. As voids grow and eventually accumulate temperature and current density increase significantly in localized regions and failure may occur.

Recently the damage induced by thermal stresses in metallisations have also been recognized as an important reliability concern, perhaps of similar gravity (4). Thermal stresses in the metallisations are caused by the different thermal expansion coefficients of the metal and the substrate. Stress induced voids and hillock formation are the main causes of interconnect failures before service. Moreover thermal stresses or thermal stress induced voids may inhance the subsequent EM damage during the service life.

Thin metallic lines deposited on Silicon are usually in a highly stressed state induced by the thermal treatments during the technological processes. The features of this state, which depend also on the line geometry, the aspect ratio and on the presence of passivating layers, are usually calculated by suitable finite elements computer codes. Also X-ray diffraction techniques are used for experimental determinations.

The thermal expansion coefficient of highly conducting metals is about one order of magnitude larger than the one of Silicon and most ceramic materials. Tensile stresses are consequently originated by cooling from the film deposition temperature, and their amplitude can exceed the elastic limit, giving rise to plastic deformation. Subsequent relaxation of the residual stresses takes place by creep phenomena which involve migration of vacancies as well as grain boundary sliding.

Stress induced grain boundary voids are generally observed after cooldown from annealing treatments at 300- 400 °C in the Aluminium based metallisations normally used in Silicon devices. This suggests that the flaws resulting by grain boundary sliding act as nucleation centers from which the voids subsequently grow. **It is remarkable that voids grow even at room temperature, so the main body of the thermal stress induced failures in these interconnects occurs within about a month from the time of fabrication.**

Depending on the level of thermal stresses and on the size of the thermally stress induced vois, thermal stress and EM interact in various forms (4). As it is well known a driving force F acting on the atoms arise in a stress field. In the purely elastic case its components can be written :

$$F_j = \Omega \sum_{i=1}^{3} \delta \sigma_{ij} / \delta x_i \quad (J = 1, 2, 3)$$

where Ω is the atomic volume.

There are two different approaches in the analysis of EM and failure: one typical of the industrial environement and one related to basic research. The former arises from the need of statistical information about the mean lifetime of a given metallisation system and of a reliability indicator. The latter aims at a more complete understanding of the phenomenon at a microscopic level.

Among the destructive tests the MTF (mean time to failure), which relies on the variables current density and temperature to determine the significant parameters of the phenomenon, is the most well known . Other related methods are BEM (breakdown energy of metals), SWEAT (standard wafer-level electromigration acceleration test) and WIJET (wafer-level isothermal Joule heated electromigration test); their description and evaluation can be found in Ref. (1).

The choice of the statistical framework for life test data analysis has been a central issue. A lognormal distribution is generally assumed in life test data as it prooved to provide better agreement than the Weibull or the logaritmic extreme value statistic (1).

Basic research utilises the techniques typical of physical metallurgy and non destructive tests. Among them very accurate resistometric methods which can determine resistance changes and the residual resistivity even during the very early stages of EM.

The rate of resistance increase is generally correlated to temperature through :

$dR / R_0 \, dt = A \exp(- E / KT)$ to determine the activation energy E and the significant parameters of the phenomenon.

These measurements provided values of E which fairly correspond to those for vacancy migration from grain boundaries (or defects) to the bulk . See e.g. the Table below which reports the activation energy values for different mechanisms in pure Al.

Diffusion mechanism	**E (eV)**
lattice (bulk)	1.4
grain boundaries	0.4 - 0.5
grain boundaries to bulk	0.62
defects to bulk	>0.62
surface	0.28

The addition of alloyng elements can shift E towards higher values nearer to the one for the diffusion in the bulk.

Aluminium alloys are usually employed in device production: the Al-Cu (up to 4 at % Cu) is the one more frequently used, leading to an increase of a factor about 80 in the MTF. Also Al-Si (1 at % Si) is used, which presents the additional advantage of avoiding further dissolution of the semiconductor in the metal film.

In both cases precipitates (Cu Al_2 and Si respectively) are present in the film after cooling, mainly located at the grain boundaries, with the result of hindering grain boundary sliding. As it was reported above this sliding is like to be the responsible for the formation of the flows which in turn nucleate the void growth. The coherency of the matrix and precipitate seems very important in this respect, incoherent particles are in fact likely to act also as nucleation centres for the voids.

Recently also Ti has been found to have beneficial effects on Al, to an extent similar to the one of Cu.

We must point out that the **beneficial influence of the alloying elements is largely attributed to their segregation at the grain boundaries**, where because of their size and other differences relative to the solvents species they will tend to reduce solvent diffusion.

The phenomena summarized in this paper have not received until now sufficient attention in P.V devices, although a significant impact can be foreseen for long life service, particularly in the photovoltaic cells designed to operate under sunlight concentration.

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