10. From these results we can see that even though the leakage current increases and the transconductance decreases, the transistors are still "alive" and operative. Thus, in the case of neutron bombardment, Al_2O_3 MOS transistors also seem to be quite "hard."

VI. Conclusion

It has been demonstrated that fabrication of MOS devices employing a gate insulator obtained by plasma anodization of evaporated aluminum is feasible. These devices exhibit excellent characteristics and are remarkably resistant to radiation.

Acknowledgment

F. Micheletti and R. Lenskold have assisted in the fabrication of the devices and in measurements; F. Kolondra carried out the bombardment and P. Rappaport gave constant encouragement.

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Electromigration—A Brief Survey and Some Recent Results

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Abstract—**Recently, electromigration has been identified as a potential wear-out failure mode for semiconductor devices employing metal film conductors of inadequate cross-sectional area. A brief survey of electromigration indicates that although the effect has been known for several decades, a great deal of the processes involved is still unknown, especially for complex metals and solute ions. Earlier design equations are improved to account for conductor film cross-sectional area as well as film structure, film temperature, and current density. Design curves are presented which permit the construction of high reliability "infinite life" aluminum conductors for specific conditions of maximum current and temperature stress expected in use. It is also shown that positive gradients, in terms of electron flow, of temperature, current density, or ion diffusion coefficient foreshorten conductor life because they present regions where vacancies condense to form voids.**

Introduction

ELECTROMIGRATION is a term applied to the transport of mass in metals when the metals are stressed at high current densities. The effect has been known for several decades and has been observed in both molten and solid metals [1]–[3]. Recently, electromigration has been recognized as a potential wear-out failure mode in semiconducting devices employing metal film conductors of inadequate cross-sectional area, and has stimulated investigations of mass transport in metal films [4]–[11]. The failure is an electrical open circuit due to the apparent loss of conductor metal. Fig. 1 presents a scanning electron micrograph of an aluminum film conductor which has failed due to this process. Several voids in the 1-mil wide aluminum stripe are seen with one void extending across the entire conductor resulting in an open circuit.

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Brief Survey

Professor Huntington and his co-workers at the Rensselaer Polytechnic Institute, Troy, N. Y., have contributed greatly to an understanding of the processes involved in electromigration; however, to date, much is still unknown [12]–[19]. The Rensselaer group studied the current induced motion of surface scratches on bulk metals, and they have concluded that a metal ion which has been thermally activated and is at its saddle point (lifted out of its potential well and is essentially free of the metal lattice), is acted on by two opposing forces in an electrically conducting single band metal. (See Fig. 2.)

Fig. 1. One-mil wide Al stripe which has failed due to void formation by electromigration.

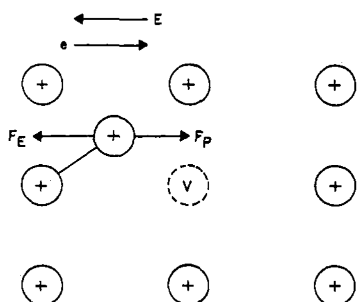

Fig. 2. Forces acting on a thermally activated ion at its saddle point in a conductor.

1) The electric field applied to the conductor will exert a force on the activated positive ion in a direction opposite to the electron flow.
2) The rate of momentum exchange between the conducting electrons colliding with the activated metal ions will exert a force on the metal ion in the direction of electron flow.

Because of shielding electrons, the force on the ion due to the electric field is quite small; therefore, the predominating force is that of the "electron wind." As a result, activated metal ions which are upstream in terms of electron flow from a vacancy have a higher probability of occupying the vacancy site than do other near neighbor ions which surround the vacancy. Metal ions, therefore, travel toward the positive end of the conductor while vacancies move toward the negative end. The vacancies condense to form voids while the ions condense at certain discontinuities to form crystals, whiskers, and nondescript hillocks. Surface scratch marks on bulk metal conductors behave as vacancies and are observed to move along the surface of the conductor in the direction of the negative terminal. The activation energy for the velocity of surface scratch motion on bulk materials was determined by the Rensselaer group to be identical to the activation energy for the lattice self-diffusion of the metals.

In more complex metals the effect of the "hole wind" on electromigration is poorly understood. For the hole conductors iron and cobalt, mass transport is in the direction of hole transport, while for the hole conductors zinc, cadmium, and lead, mass transport is in the direction of electron flow. Here, the effects of the mean-free-path length of the carriers and their effective masses appear to play an important role.

The forces exerted on solute ions, whether interstitial or substitutional, require considerably more study to be well understood. As would be predicted, however, hydrogen and deuterium dissolved in the hole conductor iron move in the direction of the hole motion, and silicon dissolved in the electron conductor aluminum moves in the direction of electron flow. This latter case has been shown to lead to another potential semiconductor device wear-out failure mode caused by the dissolution of silicon into aluminum at a contact region, and the transport of the solute ions away from the interface by the electron wind force. The process is a continuous one which leads to etch pit growth in silicon at high current density contacts where electrons leave the silicon and enter the aluminum. Failure results when an etch pit grows through a shallow underlying junction resulting in an electrical short [20].

The theory as developed for bulk materials leads to a mass transport which is a direct function of current density. The experimental work, however, was carried out only over a narrow range of current densities (1.5:1). A simple theory recently presented [8], and later slightly modified [10], [11], leads to a current density squared relationship with mass transport as shown in (1).

$$\frac{1}{\mathrm{MTF}} = AJ^2 \exp - \frac{\phi}{kT} \tag{1}$$

where

MTF = median time to failure in hours,
A = a constant which contains a factor involving the cross-sectional area of the film,
J = current density in amperes per square centimeter,
ϕ = an activation energy in electron volts,
k = Boltzman's constant, and
T = film temperature in degrees Kelvin.

Experiments carried out with readily cooled metal films enabled the experimental current density to range greater than 5:1 and appear to confirm the J^2 relationship.

It was also shown that the activation energy for electromigration was strongly dependent upon the structure of the film [8]. Small crystallite (1.2 μ) aluminum films enabling ion diffusion to take place in the grain

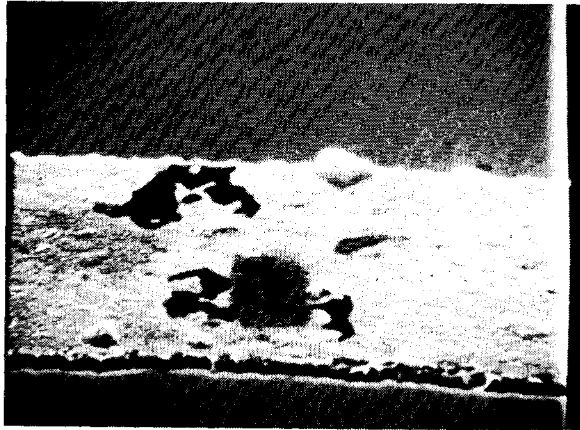

Fig. 3. Voids formed in a ½-mil wide small-grain Al film.

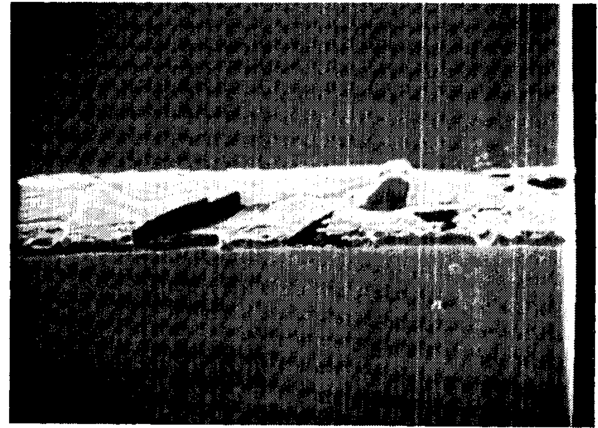

Fig. 6. Void and hillock growth in a ½-mil wide large-grain Al film.

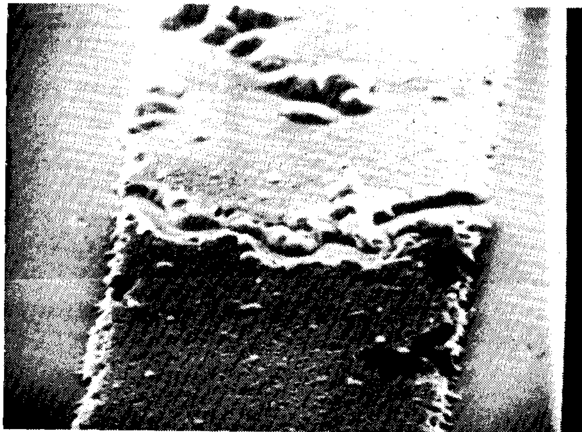

Fig. 4. Voids, hillocks, and an open circuit in a ½-mil wide small-grain Al film.

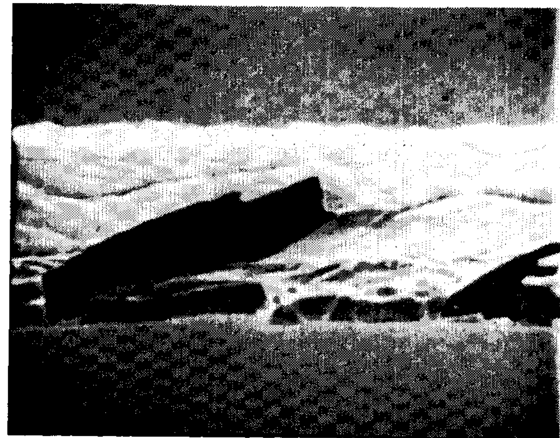

Fig. 7. Enlarged view of a void in a large-grain Al film.

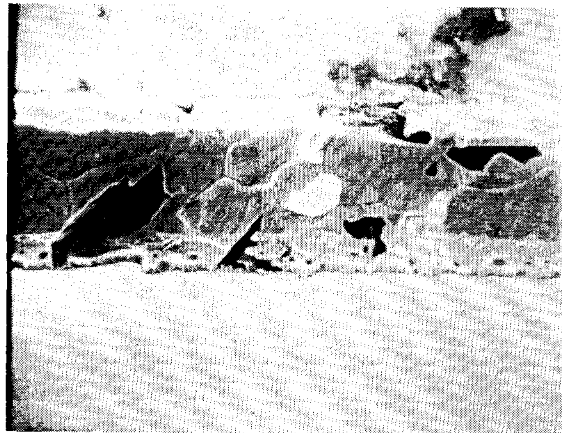

Fig. 5. Void growth in a ½-mil wide large-grain Al film.

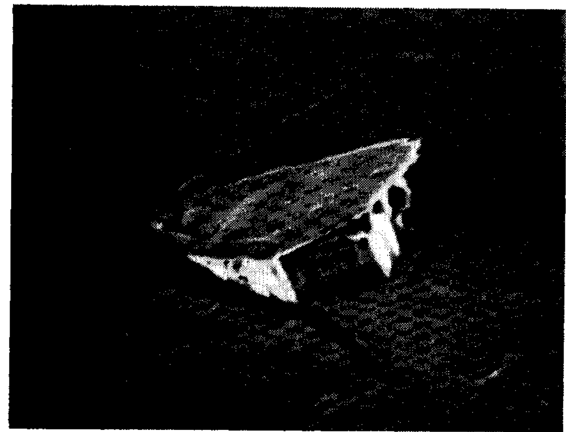

Fig. 8. Hillock formation in large-grain Al film with a glass film overcoat.

boundary and over the surface as well as through the lattice exhibited an activation energy of 0.48 eV.

An electron photomicrograph of voids growing in such a small-grained film stressed at elevated current density (10^6 A/cm^2) is shown in the scanning electron micrograph (SEM) of Fig. 3. The film is 0.5 mils wide and both grain boundary and surface diffusion appear to be the predominant transport mechanisms. A typical void which has resulted in an open circuit in such a film is shown in the SEM of Fig. 4. After extensive growth of voids, the remaining aluminum filaments appear to fuse at high current densities to form an open circuit.

Well-ordered, large-grained aluminum films where ion diffusion could take place mainly over the surface and through the lattice exhibited an activation energy for electromigration of 0.84 eV. The increase in activation energy to 0.84 eV for these well-ordered, large-grain films is attributed to the reduction of grain boundaries with their associated low energy diffusion paths.

Fig. 5 is a SEM of a typical large-grained film after stress. Surface diffusion appears to be a predominant transport mechanism since the large area voids which form are not associated with the grain boundaries. A better view of the hillocks which grow out of the surface of the film is shown in Fig. 6. An enlarged view of one of the voids in Fig. 7 clearly shows the void to grow from the top surface indicating surface diffusion to predominate.

Large-grained aluminum films 12 000 Å thick coated with a film of SiO_2 in an attempt to reduce surface as well as grain boundary diffusion exhibited an activation energy for electromigration of 1.2 eV. The increase in activation energy over that of the well-ordered but non-glassed films is attributed to the reduction of surface diffusion due to the overlaying glass film. The activation energy of 1.2 eV approaches that of the lattice self-diffusion of aluminum determined by quenching techniques of 1.48 eV [21].

Fig. 8 shows an SEM of a hillock which has broken through the glass overlay. The broken glass film remains intact on top of the hillock indicating that the hillock grows from the base.

Effect of the Conductor Cross-Sectional Area on Lifetime

In the derivation of the simple theory, the median time to failure was considered to be inversely related to the rate of mass transport. A constant for this relationship included a factor which would account for the conductor cross-sectional area. As a first approximation it would be predicted that for a given rate of mass transport, the lifetime of the conductor should be a direct function of the conductor cross-sectional area. In the experiment reported previously it was determined that the equation

$$\frac{1}{J^2\,\mathrm{MTF}} = 5.18 \times 10^{-6} \exp - (0.84/kT) \tag{2}$$

held for large-grained films 6000 Å thick and 16.25 μ wide. When the preexponential constant is normalized to the conductor cross-sectional area of 9.65×10^{-8} cm^2 the above equation can be written as:

$$\mathrm{MTF} = \frac{(w)(t) \exp (0.84/kT)}{5 \times 10^{-13} J^2} \tag{3}$$

where w and t are the conductor width and thickness expressed in centimeters.

To test the effect film cross-sectional area has on film lifetime, two additional experiments were made. In the first experiment large-grained films of constant thickness near 7000 Å but possessing varying linewidths from 11.5 to 50.3 μ were tested at elevated current densities and temperatures. The results of this experiment are shown in Fig. 9 which plots the experimentally determined lifetime against the predicted lifetime using (3). The 1:1 correspondence indicates that the lifetime of films is a direct function of the film cross-sectional area over the indicated range of conductor widths.

The second experiment tested large-grained aluminum films of nearly constant linewidths of about 12 μ and thicknesses varying from 1921 to 12 540 Å. The results of this test are shown in Fig. 10 which again plots the experimentally determined life against the predicted lifetime using (3). It is concluded that film lifetime is a direct function of the film cross-sectional area.

Normalizing the equations which have previously been experimentally determined (and reported at an earlier date) to express the behavior of small crystal, large crystal, and glassed large crystal films of specified cross sections results in the following equations:

small crystallite films (1.2 μ)

$$\frac{wt}{J^2\,\mathrm{MTF}} = 2.43 \times 10^{-16} \exp - (0.48/kT) \tag{4}$$

or

$$\mathrm{MTF} = \frac{wt \exp (0.48/kT)}{2.43 \times 10^{-16} J^2}; \tag{5}$$

large crystallite films (8 μ)

$$\frac{wt}{J^2\,\mathrm{MTF}} = 5 \times 10^{-13} \exp - (0.84/kT) \tag{6}$$

or

$$\mathrm{MTF} = \frac{wt \exp (0.84/kT)}{5 \times 10^{-13} J^2}; \tag{7}$$

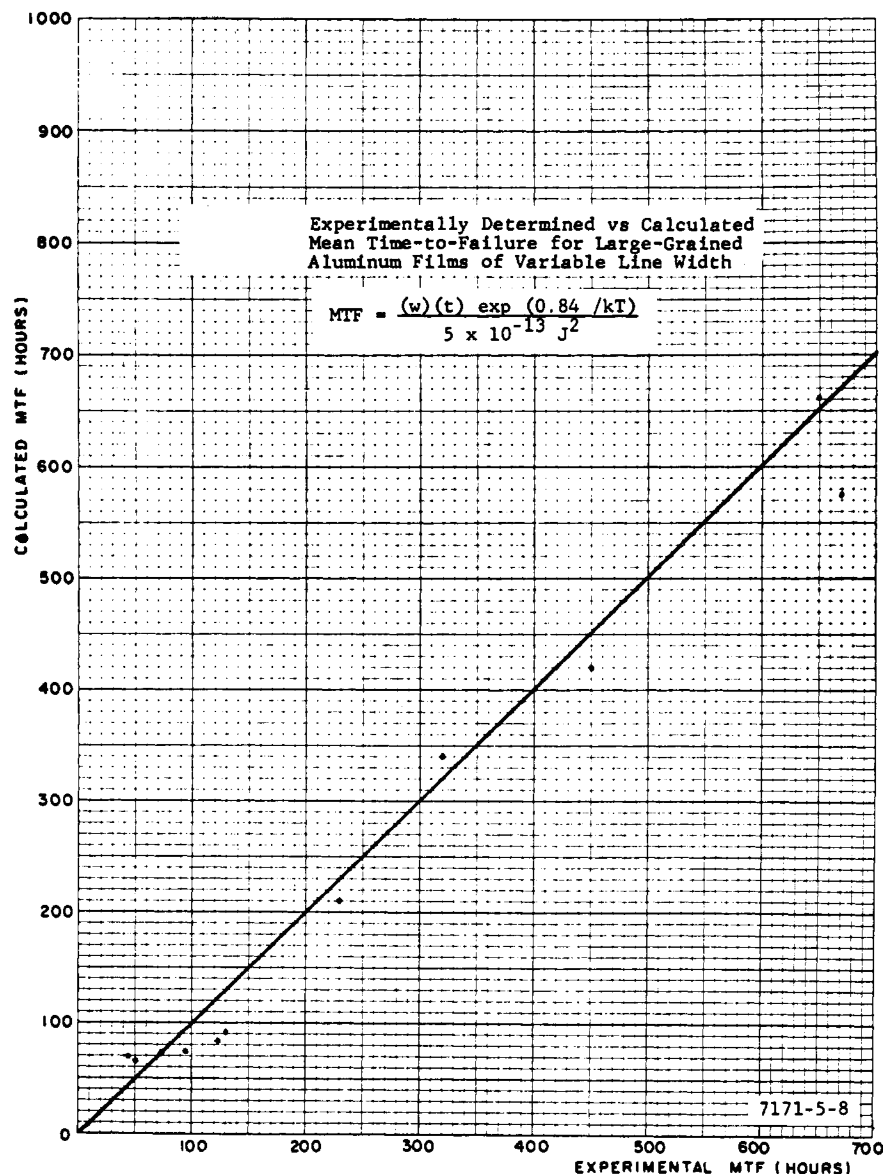

Fig. 9. Experimentally determined versus calculated mean time to failure for large grained aluminum films of variable line width.

large crystallite glassed films

$$\frac{wt}{J^2\,\mathrm{MTF}} = 8.5 \times 10^{-10} \exp - (1.2/kT) \qquad (8)$$

or

$$\mathrm{MTF} = \frac{wt \exp (1.2/kT)}{8.5 \times 10^{-10} J^2}\,. \qquad (9)$$

This normalized data plotted as a composite Arrhenius plot is given in Fig. 11. As shown, these intersect at a temperature near 275°C. At this temperature and above, lattice diffusion is predominant over surface and grain boundary diffusion processes; thus, film structural effects are not important in that temperature range. At temperatures lower than 275°C, however, orders of magnitude improvement in lifetime can be obtained through the use of large grain or large-grain glassed films.

Design graphs are presented in Figs. 12, 13, and 14 where the cross-sectional film area has been chosen to be 10^{-7} cm² and is typical for conductor stripes for integrated circuits. Since the lifetime is directly proportional to the film cross-sectional area the lifetime of films of other cross-sectional areas can also quickly be determined.

The Effect of Gradients on Conductor Lifetime

In the above discussion, equations were developed which express the lifetime of long aluminum conductors which contain no gradients of temperature, current density, or ion diffusion coefficient. If gradients exist as defined in Fig. 15 it would be expected that hillocks and voids would preferentially grow at the positions

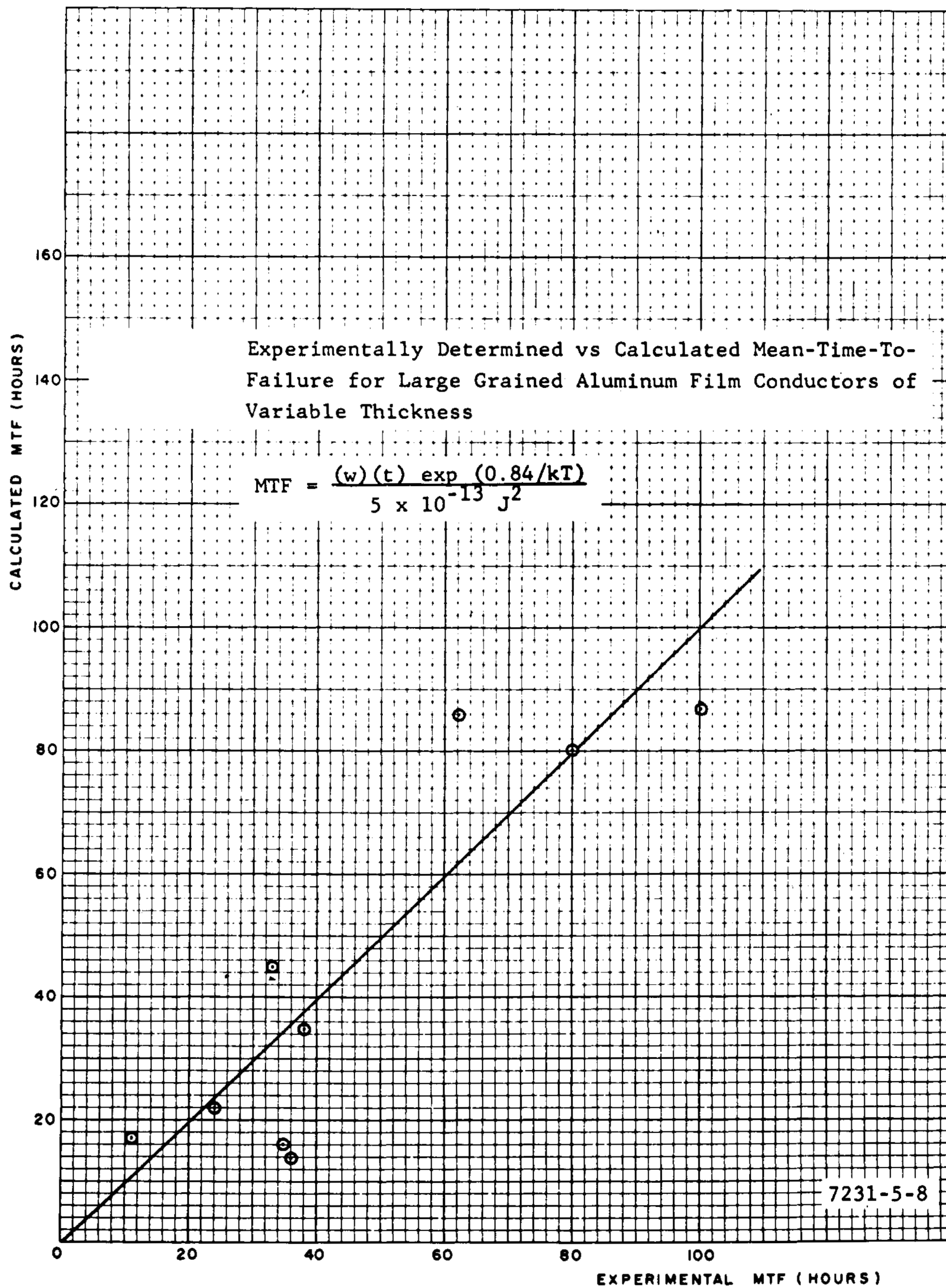

Fig. 10. Experimentally determined versus calculated mean time to failure for large grained aluminum film conductors of variable thickness.

indicated in that figure. This is because aluminum ions in the plateau moving to the right arrive at the negative gradient faster than they are removed from that region. The aluminum ions therefore accumulate in this region and form crystals, whiskers, or nondescript extruded appearing formations just upstream (in terms of electron flow) from a negative gradient. In a similar manner, aluminum ions just downstream from a positive gradient are removed from that region faster than they are replaced by ions from further upstream. The resultant excess vacancies condense at that point to form voids. In addition, voids and whiskers form more slowly in gradient-free regions because vacancies generated by ions flowing downstream are readily filled by ions moving from upstream portions of the conductor.

Films containing positive gradients of temperature, current density, or ion diffusion coefficient would be expected to fail earlier than would be predicted by the equations generated in the previous section of this paper. This is due to the presence of regions where

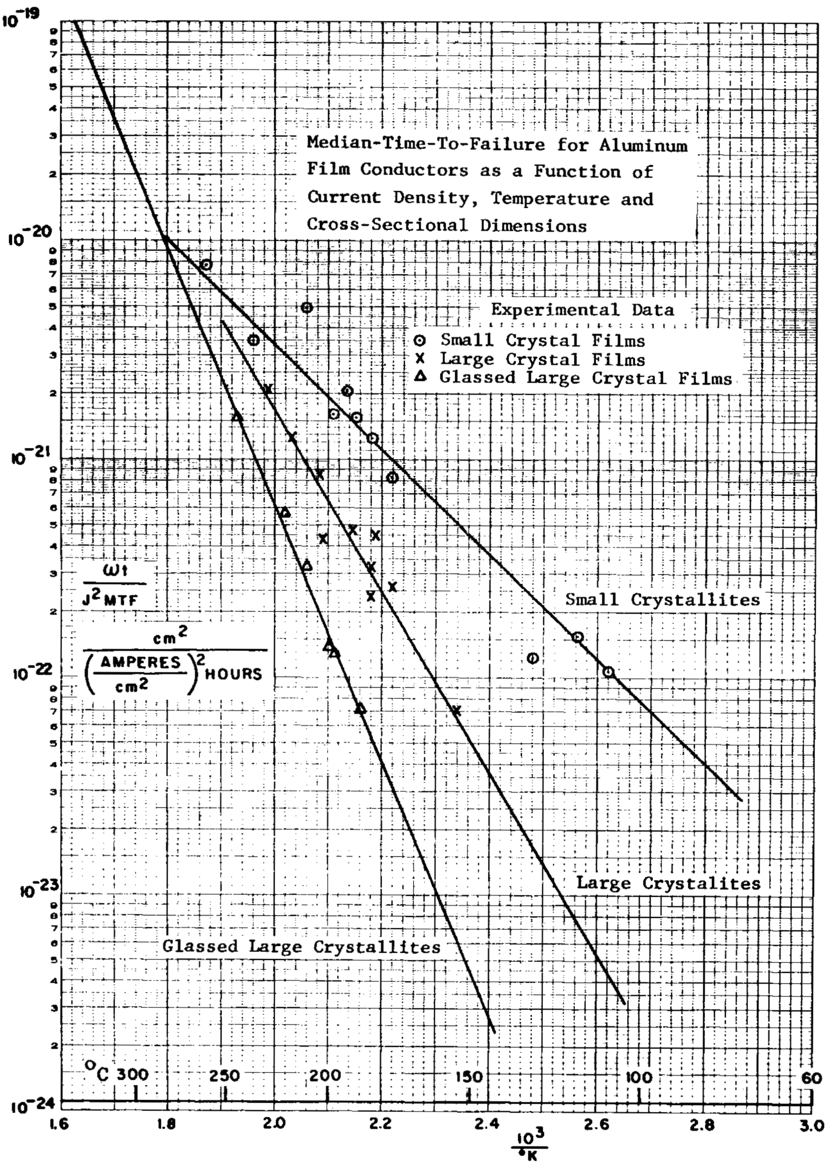

Fig. 11. Mean time to failure for aluminum film conductors as a function of current density, temperature, and cross-sectional dimensions.

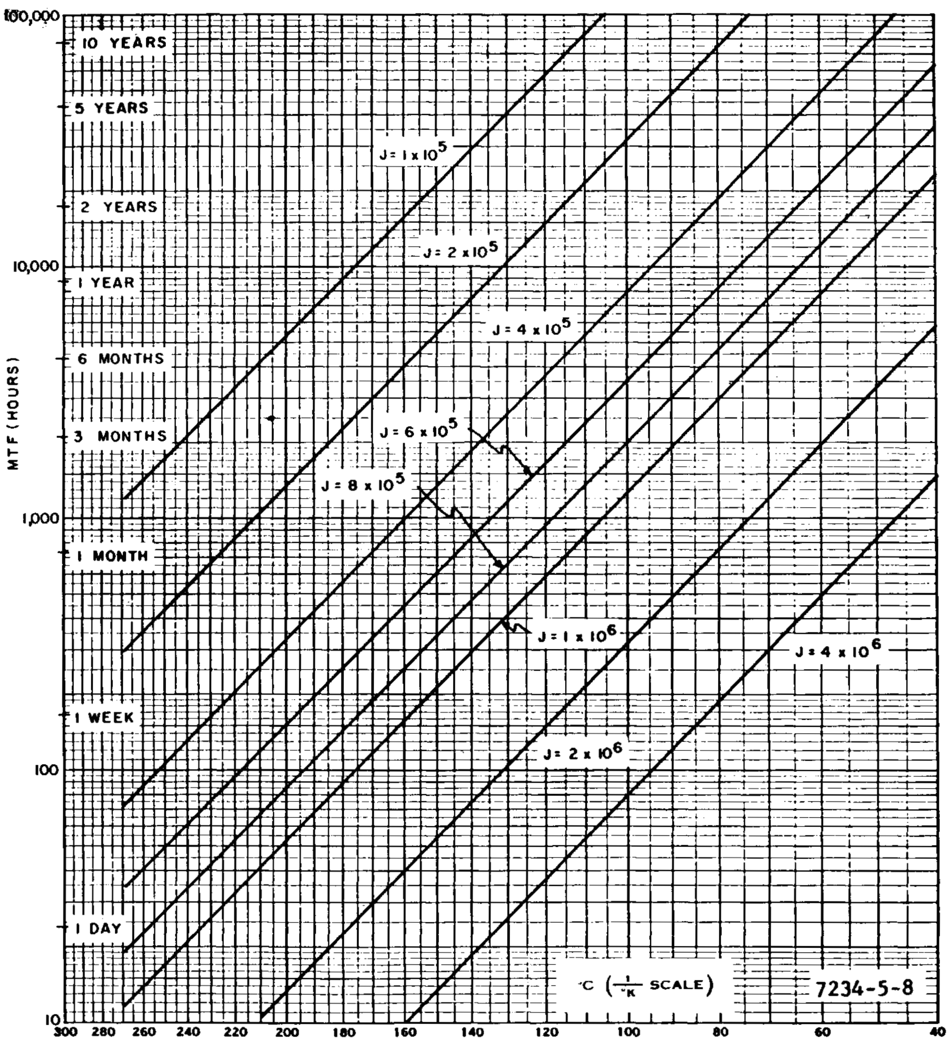

Fig. 12. Small crystallite aluminum film lifetime of conductors with 10^{-7} cm^2 cross-sectional area.

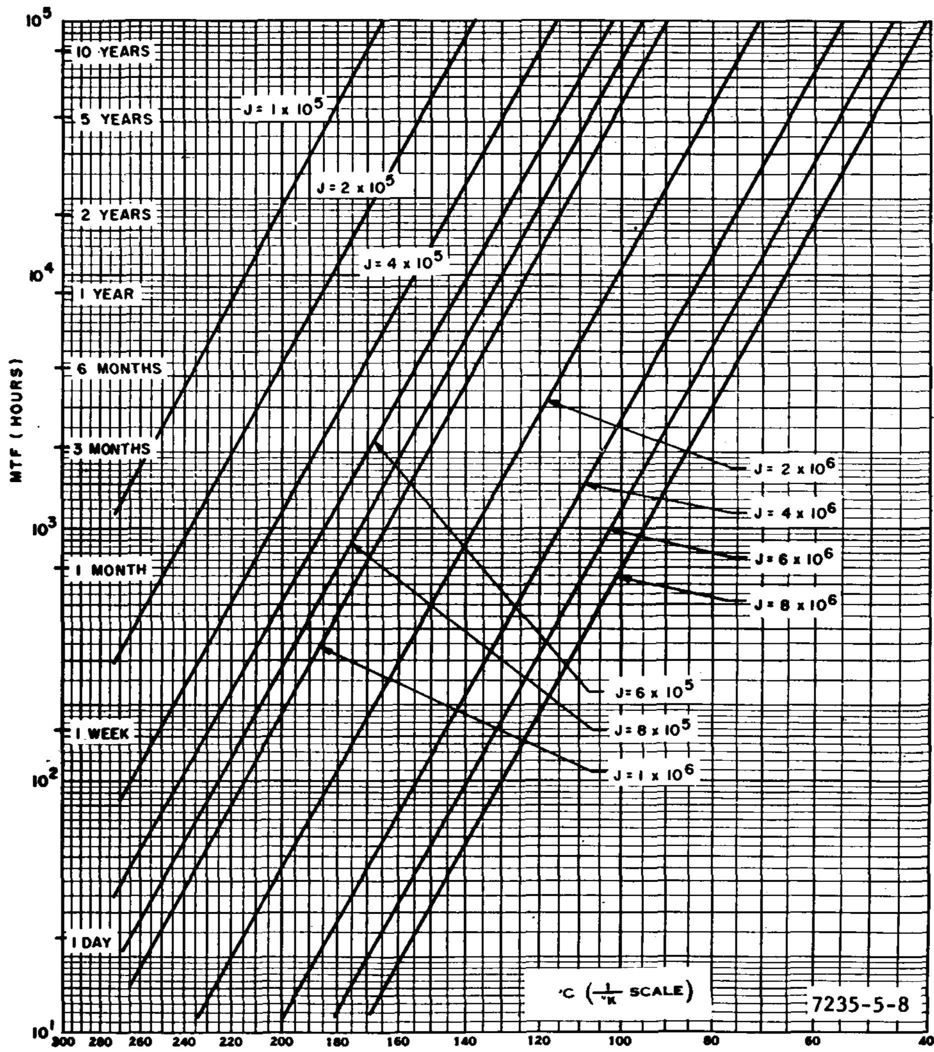

Fig. 13. Large crystallite aluminum film lifetime of conductors with 10^{-7} cm² cross-sectional area.

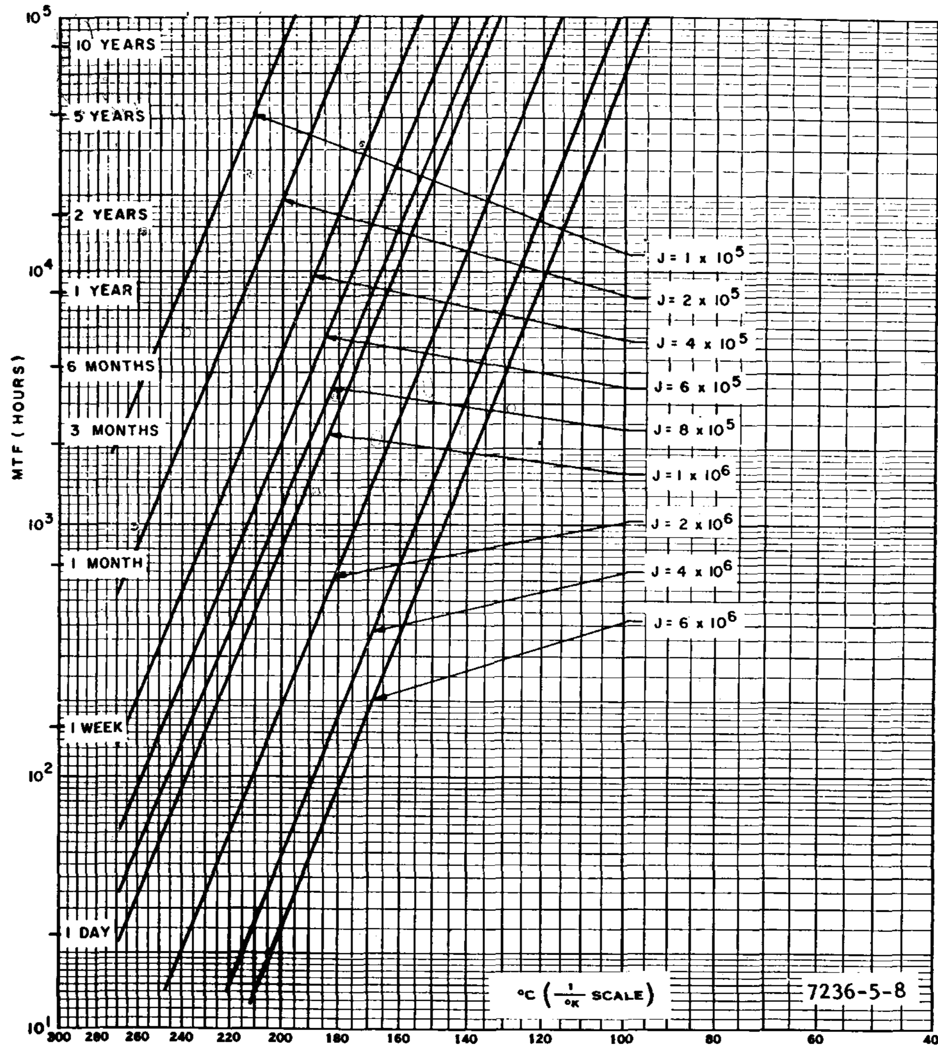

Fig. 14. Classed large crystallite aluminum film lifetime for conductors with a cross section of 10^{-7} cm².

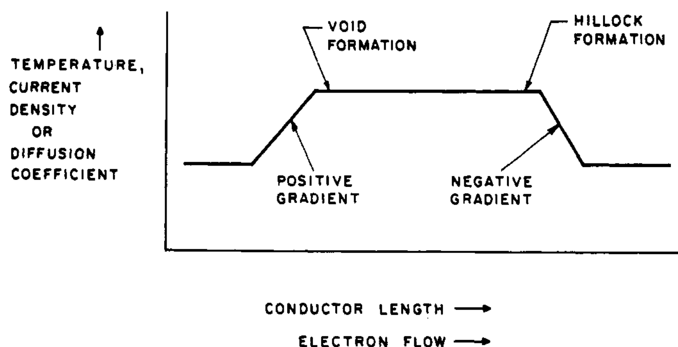

Fig. 15. Definition of gradients.

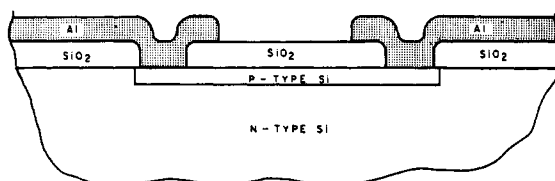

Fig. 16. Cross section of silicon diffused resistor contacted with aluminum electrodes.

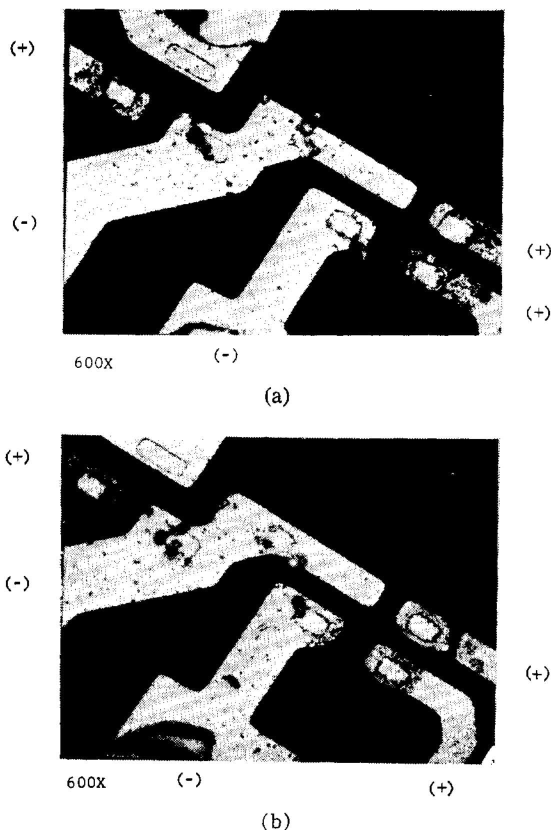

Fig. 17. Aluminum contacts to silicon diffused resistors after aging at $J = 1.3 \times 10^5$ A/cm² and 235°C for 250 hours.

vacancies condense to rapidly form voids which quickly lead to an open circuit. To test the effect gradients in conductor ion diffusion have on conductor lifetime, test vehicles were made in which the conductor material composition was changed abruptly. This was done by contacting resistors diffused into silicon by aluminum conductors as depicted in the cross-sectional diagram of Fig. 16. The diffused resistors are silicon doped with a p-type impurity and are typical of resistors used in silicon integrated circuits.

An array of three test resistors was evaluated by stressing the aluminum for 230 hours at current densities of 1.3×10^5 A/cm² and conductor temperatures of 235°C. Fig. 17 shows two sets of three resistors after aging at the above conditions. Whiskers and hillocks grow (out of focus) from the negative resistor contact regions, while voids, some of which grow to form open electrical circuits, develop at the positive resistor terminals.

A second set of similar resistors stressed in a like manner is shown in Fig. 18. The electrical stress polarity of these resistors, however, has been reversed from the previous set. Again, hillocks and whiskers form at the negative resistor terminals and voids form near the positive resistor terminals as was predicted. By comparison with the previous figure it is seen that the formation of hillocks and voids near the contacts is determined by the direction of electron flow and serves as additional proof that the direction of mass transport of aluminum is in the direction of electron flow.

A scanning electron photomicrograph (SEM) of a similar sample (Fig. 19) shows extensive whisker growth at the negative terminals of two of these resistors. One whisker is nearly 5.5 mils long. An enlarged SEM photomicrograph of this region is presented in Fig. 20. Here the "hillocks" appear to be extruded from the aluminum film surface. The relative heights of the alu-

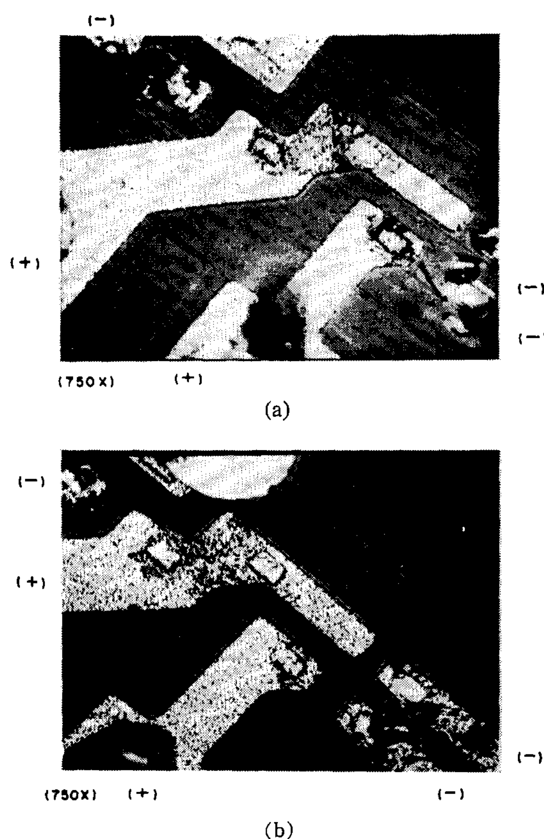

Fig. 18. Al contacts to Si diffused resistors after aging at $J = 1.3 \times 10^5$ A/cm² at 235°C for 230 hours.

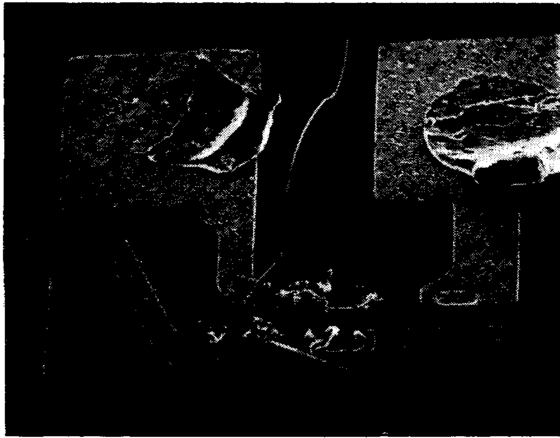

Fig. 19. Whisker and hillock growth at negative Al contacts to Si diffused resistors (ohmic hole in glass is 0.5 by 0.3 mil).

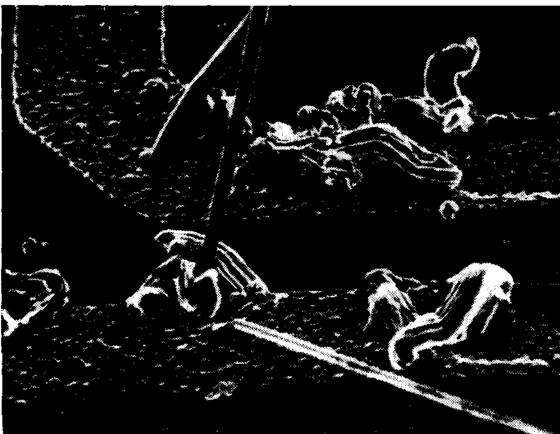

Fig. 20. Enlarged view of whisker and hillock growth at negative Al contacts to Si diffused resistors.

Fig. 21. Void formation in positive Al contacts to silicon diffused resistors (ohmic hole in glass is 0.5 by 0.3 mil).

minum film and of the hillocks indicates extensive mass transport of the aluminum to these regions.

A SEM photomicrograph of the positive terminals of two of the resistors is shown in Fig. 21. At these terminals electrons leave the silicon and enter the aluminum. The depletion of the aluminum forms a void which results in an open circuit, as is clearly indicated.

Conclusions

Electromigration has been identified as a potential wear-out failure mode for semiconductor devices possessing conductors of inadequate cross-sectional area. Although electromigration in metals has been known for several decades it is still not well understood. Design equations have been presented which enable the construction of long line aluminum conductors with essentially infinite lifetime. This is based upon the structure of the aluminum, the current density, conductor temperature, and conductor cross-sectional area. It has also been shown that a positive gradient (in terms of electron flow) in the diffusion coefficient of the metal ions produces a region where vacancies condense to form voids and greatly reduce film life. It is predicted that similar gradients in temperature and current density will also reduce film life.

Acknowledgment

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