MASS TRANSPORT OF ALUMINUM BY MOMENTUM EXCHANGE WITH CONDUCTING ELECTRONS

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SUMMARY

A failure mode commonly found in high power devices and integrated circuits appears when aluminum conductors carry current densities in excess of 10^5 amperes per square centimeter at temperatures above 100°C. The mode of failure is an open circuit which often is observed as a "crack" in the aluminum and is commonly referred to as "cracked stripe" or "disappearing aluminum." This paper presents a study of this failure mode which has been identified with the mass transport of aluminum by momentum exchange between activated aluminum ions and conducting electrons. The activation energy for the reaction has been obtained and equations relating temperature, current density and film structure to conductor life are presented. The activation energy appears to be identical to that for the lattice self-diffusion of aluminum modified by factors involving both surface diffusion and grain-boundary diffusion. These latter two factors are important in films formed by the condensation of aluminum vapor.

INTRODUCTION

This paper presents a study of a failure mode commonly found in high power devices and integrated circuits where aluminum conductors carry current densities in excess of 10^5 amperes per square centimeter at temperatures above 100°C. The mode of failure is an open circuit caused by the movement of aluminum ions in the direction of electron flow. Voids in the metal, resulting from this process, tend to grow in a direction normal to the current flow. The effect is an accumulative one increasing the local current density in the region of the void thus accelerating the process. The end result is a void extending entirely across the film interrupting the current flow. This frequently occurs in emitter stripes where the stripe thickness is reduced as it extends over a step in the glass surface. Under the step at this point there generally exists a junction in the silicon which dissipates power thus aggravating the situation by increasing the local temperature.

Figure 1 (a) shows a photomicrograph of a ½-mil-wide aluminum stripe after it had been stressed at a current density of 1.5×10^6 A/cm^2 at 190°C. Voids are shown growing at the edges and in the center of the film. Also nodules and crystallites of aluminum grow (out of focus) from the film appearing as dark areas. One void has extended nearly half way across the conducting stripe. Aluminum ions are transported away from certain crystallites and hang up on other sites growing well defined crystals or nondescript nodules. Nodule or crystal growth appears downstream in terms of electron flow from voids. The voids and growth regions are rather uniformly distributed over the length of the conductor stripe when the entire stripe is at an elevated temperature.

Figure l(b) shows extensive surface reordering and a large crystalline whisker of aluminum extends roughly in the plane of the film. A large void also appears along one edge of the film near the center of the picture.

Figure 2(a) is a photomicrograph of a current stressed aluminum film showing the characteristic angular void formation as well as a

(a)

(b)

Figure 1. Stressed Aluminium Films Showing Voids and Crystal Growth

large whisker growing slightly out of the plane of focus of the picture. The heavy dark spots are also whiskers growing normal to the plane of the film and are therefore out of focus. This film was stressed at a current density of 1.2×10^6 A/cm^2 at a film temperature of 186°C for 47 hours.

A view of a similarly stressed film at lower magnification is shown in Figure 2(b) where several whiskers appear. One of these has twined and then retwined to grow again in its original direction.

Professor Huntington and co-workers at the Rensselaer Polytechnic Institute have studied the current induced motion of surface scratches on bulk metals.[1],[2],[3] They have generally concluded that metal ions which are thermally "activated" (lifted out of the potential well

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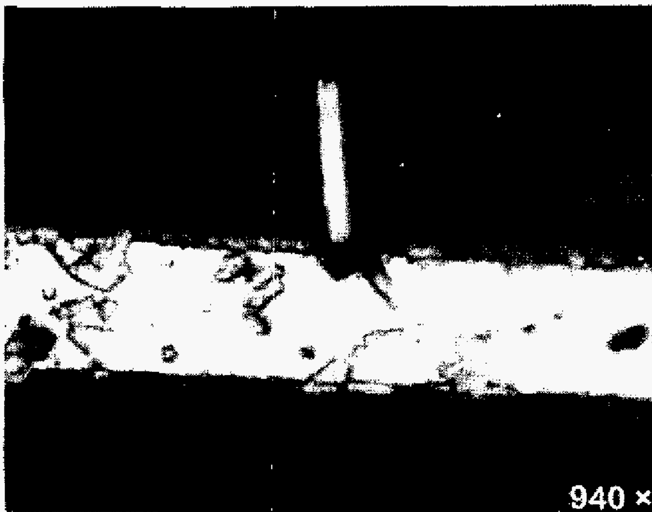
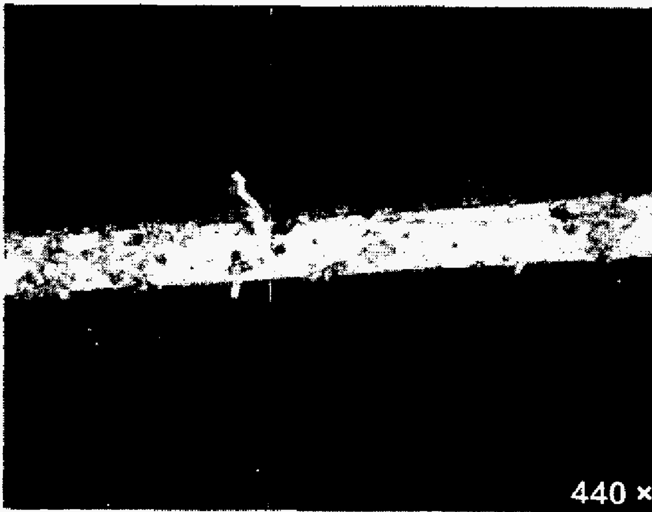


(a)



(b)

Figure 2. Stressed Aluminium Films Showing Voids and Crystal Growth

associated with the metal crystal lattice and free to move back into their original potential well or into other potential wells associated with the crystal or neighboring crystals) are acted on by two opposing forces in an electrically conducting metal:

(a) The electric field applied to the conductor will exert a force on the activated ion in the direction opposite to electron flow.
(b) 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.

The ion drifts, then, in the direction of the predominating force which at moderate temperatures for the metals investigated is in the direction of electron flow. Metal ions are observed to travel toward the positive end of the conductor while vacancies move toward the negative end. Scratch marks on bulk metal behave as vacancies and are therefore observed to move along the surface of the conductor in the direction of the negative terminal.

The activation energy for the velocity of scratch motion in the bulk materials observed by the Rensselaer Polytechnic Institute Group was the same as the activation energy for the lattice self-diffusion of the metals. The velocity of scratch motion was also concluded to be a direct function of current density, however only a small variation in current density was reported in their experiments.

Based upon the above work, an experiment was designed to study the failure rate of long thin aluminum film conductor stripes stressed at various current densities and temperatures. Since the aluminum films were formed by the condensation of the vapor in a vacuum ambient, it was anticipated that the activation energy for the failure mode would be less than that of bulk aluminum and highly dependent upon the degree of crystalline order of the film.

Highly polycrystalline films formed by vacuum deposition from tungsten filaments onto cold substrates were suspected of exhibiting very low activation energies due to grain-boundary diffusion and surface diffusion. Well ordered films deposited on heated substrates and possessing large area crystallites should exhibit a moderate activation energy for the failure mode, being depressed from the activation energy due to lattice diffusion mainly by surface diffusion which, for thin films, is important because of their large surface-to-volume ratio. Films deposited with high crystalline order and coated with a glass film in an attempt to reduce the surface diffusion were expected to possess an activation energy for this failure mode approaching that for the lattice self-diffusion of aluminum of 1.4 eV determined by nuclear relaxation measurements.

SIMPLE THEORY

The mean energy accepted by a conducting electron when falling through a potential field over its mean free path is

$$\text{electron volts} = E\lambda$$

where E is the field intensity and λ is the mean free path of the electron.

For typical mean free path lengths on the order of 5×10^{-5} cm the mean energy of the electron at a current density of 10^6 A/cm^2 in aluminum is only 1.3×10^{-4} electron volts.

$$\begin{aligned} E\lambda &= \rho J\lambda \\ &= (2.7 \times 10^{6} \text{ ohm cm}) \\ &\quad (10^{6} \text{ A/cm}^2).\ (5 \times 10^{-5} \text{ cm}) \\ &= 1.3 \times 10^{-4} \text{ eV} \end{aligned}$$

This is small compared to the activation energy required for the self-diffusion of aluminum in aluminum[4] of 1.4 ± 0.1 eV determined by nuclear magnetic relaxation measurements. The electron energy is also small compared to the activation energy for vacancy formation in aluminum of 0.5 to 1 eV. [5],[6]

The electron energy picked up by falling through the field is also small compared to the average energy due to thermal agitation at 200°C of 4×10^{-2} eV.

The electric field imposes only a slight drift velocity to the electrons in the metal in the direction of electron flow. This additional energy is not sufficient to lift the metal ions out of the crystalline lattice but can impart upon collision with a thermally activated ion momentum causing ionic drift in the direction of electron flow.

If the net force on the activated ion (total momentum transferred per sec.) directed toward the positive electrode by momentum exchange with electrons exceeds the force on the ion due to the electric field, the aluminum ion will tend to drift toward the positive electrode. If, however, the force on the ion due to the electric field exceeds that due to electron-ion momentum exchange rate, the ion will tend to drift toward the negative electrode.

If the electrons at zero field are considered to have an entirely random motion, and again a random motion after being accelerated and colliding with ions with nearly elastic collisions (the electron energy picked up from the field and delivered to the ions is small

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compared to the average thermal energy) the electrons impart all of their momentum to the ions. The rate of reaction which takes place in the migration of aluminum by momentum transfer between thermally activated ions and the electrons should then be a function of the number of activated ions or "targets" available per cm^3, the number of electrons per second available for striking the activated ions and the momentum of these electrons. This may be expressed as:

$$R = F\ (\text{electron momentum})\ (\text{number of striking electrons})\ (\text{effective target cross section})\ (\text{target density}) \quad (1)$$

where R is the reaction rate and F is a constant.

The additional momentum P picked up by an electron falling through an electric field a distance of its mean free path λ, with an average velocity v is

$$P = eE\frac{\lambda}{v} = e\rho J\frac{\lambda}{v} = e\rho J\tau \quad (2)$$

where τ is the mean free time between collisions, e is the charge on an electron, ρ is the volume resistivity and J the current density.

The electron arrival rate is related to J by

$$J = \frac{\text{coulombs}}{cm^2\,sec} = \frac{\text{number of electrons}}{6.25\times10^{18}\ cm^2\,sec}$$

or

$$\frac{n}{cm^2\,sec} = 6.25\times10^{18} J = \frac{J}{e} \quad (3)$$

One may consider the number of activated ions in the metal to follow the Arrhenius equation as a function of temperature. Thus:

$$\text{Target density} = F_1\, e^{-(\phi/kT)} \quad (4)$$

Since the mean time to failure in hours (MTF) is related to rate of mass transfer by

$$\frac{F_2}{MTF} = R \quad (5)$$

we may rewrite the expression for rate (Equation 1) by substituting Equations 2, 3, 4, and 5.

$$\frac{F_2}{MTF} = \left[e\rho J\frac{\lambda}{v}\right]\left[\frac{J}{e}\right](\sigma)\left[F_1 e^{-\frac{\phi}{kT}}\right]$$

$$= \left[\rho\frac{\lambda}{v}\sigma J^2\right]\left[F_1 e^{-\frac{\phi}{kT}}\right] \quad (6)$$

where σ = ionic scattering cross section. By consolidation of the physical constants,

$$\frac{1}{MTF} = AJ^2 e^{-\left(\frac{\phi}{kT}\right)} \quad (7)$$

The constant A embodies several physical properties including:

(a) the volume resistivity of the metal

(b) the electron free time between collisions or the electron free path and average velocity

(c) the effective ionic. scattering cross section

(d) the frequency factor for the self-diffusion of aluminum in aluminum

(e) a geometric factor relating rate of mass transfer with mean time to failure.

A more elegant derivation of the above equation is discussed in the appendix.

It would be expected that the plot of $\ln\frac{1}{MTF\,J^2}$ vs 1/T°K would be a negative straight line if the factors which contribute to A are slowly varying functions of T. The activation energy derived from the slope of this line would also be expected to be less than 1.4 eV reported for bulk aluminum due to the large surface to volume ratio of the films and the generally small crystalline size of condensed aluminum films. This is because surface diffusion coefficients are greater than grain boundary diffusion coefficients which in turn are much greater than lattice diffusion coefficients. The activation energy determined experimentally from the mean time to failure data should serve as a quality figure relating to the degree of perfection of evaporated films.

EXPERIMENTAL RESULTS

Small Crystallite Aluminum Films

An experiment was designed to determine the values of ϕ and A for highly polycrystalline aluminum films. These were deposited in a high vacuum at the low 10^{-8} Torr pressure range by the evaporation of 99.999 percent aluminum from tungsten filaments onto a cold (<100°C) substrate. The crystallite lateral size was about 1.2 microns. The substrate consists of 9000 Å of SiO_2 on silicon wafers. The films were etched to form conductor paths 54 × 0.5 mil × 7000 Å, and brazed into TO-5 headers. These were wire-bonded using 0.001-inch diameter aluminum wire, and a can was welded to the header encapsulating the film in a dry nitrogen ambient. Each cell consisted of 10 devices from which the mean time to failure was determined. The current density varied from 0.5 to 2.88 × 10^6 A/cm^2 and the mean time to failure ranged from 1.5 to 850 hours. The film temperature was determined by the oven temperature plus the rise in temperature due to film power dissipation.

A plot of $\ln\frac{1}{MTF\,J^2}$ vs $\frac{1}{°K}$ is presented in Figure 3. Except for two maverick points where the raw data on failure rate was difficult to evaluate, a straight line fits the data quite well. For these data the current density varied greater than 5 to 1 while the temperature varied 1.4 to 1 on the Kelvin scale. The equation representing this line is

$$\frac{1}{MTF\,J^2} = 2.28\times10^{-9} e^{-(0.48/kT)}$$

The activation energy of 0.48 eV is 34 percent of that reported for the self-diffusion of aluminum in aluminum of 1.4 eV.

Large crystallite Aluminum Film

Data has been gathered on the life of well ordered aluminum film conductors containing large crystallites. The films were deposited from tungsten filaments in the low 10^{-8} Torr region using aluminum source material which was 99.999 percent pure. The large crystallites (approximately 8 microns lateral geometry) were obtained by maintaining the substrate temperature at 400°C during the deposition. The film thickness was 6000 Å and the line width was in excess of 0.6 mils. The cells were stressed at current densities ranging from 0.55 to 2.02 × 10^6 A/cm^2 and the mean time to failures ranged from 12 to 1125 hours. The data for this film structure presented in Figure 4 indicates the formula relating current density and temperature to mean-time-to-failure to be

$$\frac{1}{J^2\,MTF} = 5.18\times10^{-6} e^{-(0.84/Kt)}$$

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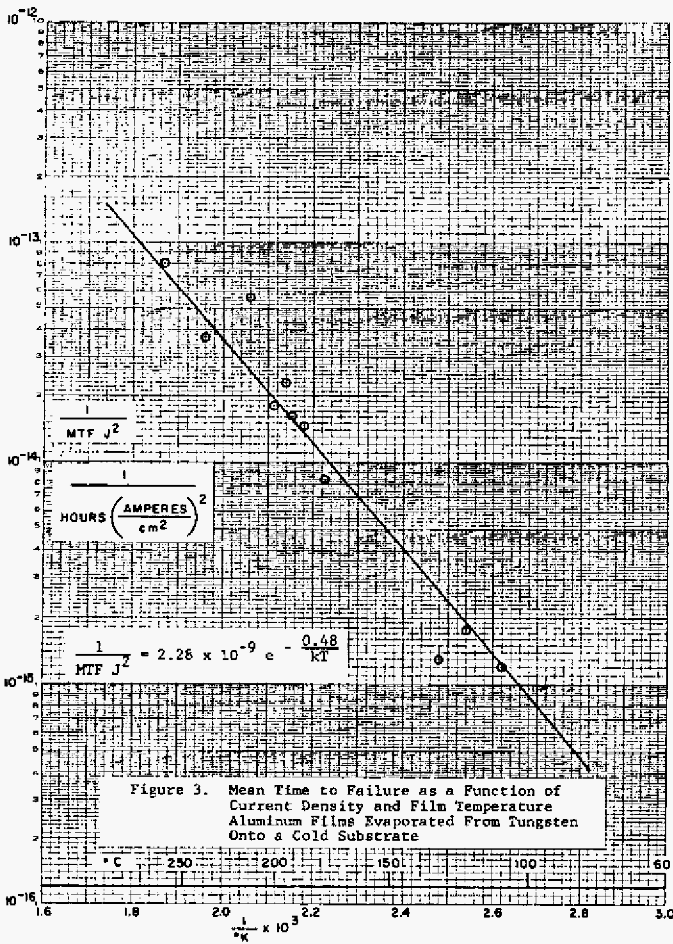

Figure 3. Mean Time to Failure as a Function of Current Density and Film Temperature Aluminum Films Evaporated From Tungsten Onto a Cold Substrate

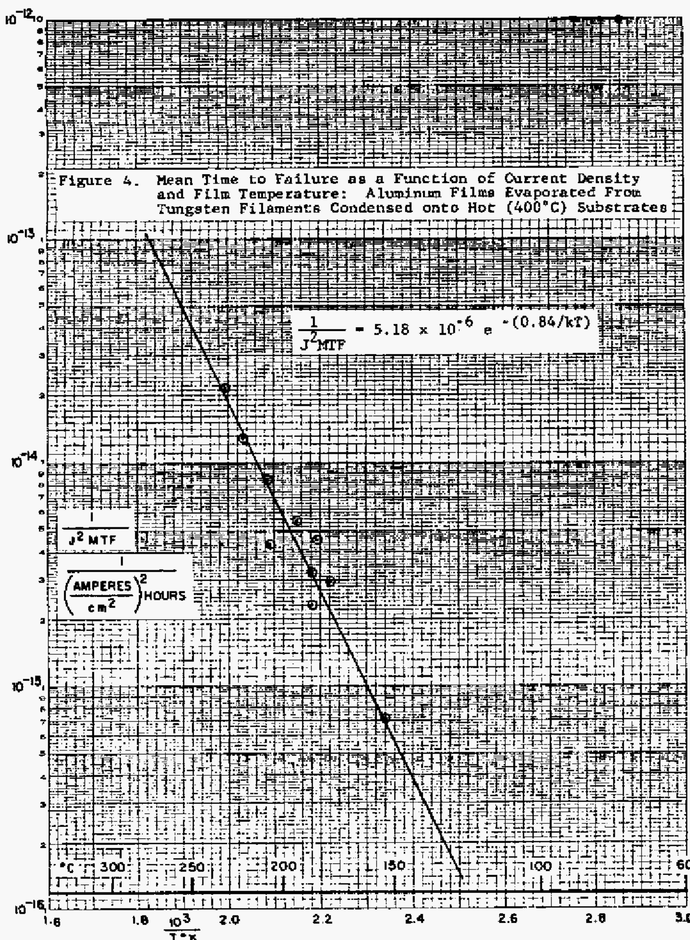

Figure 4. Mean Time to Failure as a Function of Current Density and Film Temperature: Aluminum Films Evaporated From Tungsten Filaments Condensed onto Hot (400°C) Substrates

The increase in activation energy for this failure mode for the large crystallite well ordered films over the activation energy of fine grained aluminum films is attributed to the reduction of grain boundaries which possess a high self-diffusion coefficient.

Figure 5 presents the mean time to failure, film temperature and current density relationships for both large crystallite and fine crystallite films for cross-sectional geometries indicated in the above two experiments. The crystallite lateral sizes were about 8 and 1.2 microns respectively for each film type. It is seen that there is little effect on life-time due to crystallite size at 270°C. At this temperature lattice diffusion effects predominate over grain boundary effects. As the film temperature is reduced from 270°C the film crystallite size becomes important. At a film temperature of 70°C about two orders of magnitude improvement in mean-time-to-failure can be gained through the use of large crystallite films.

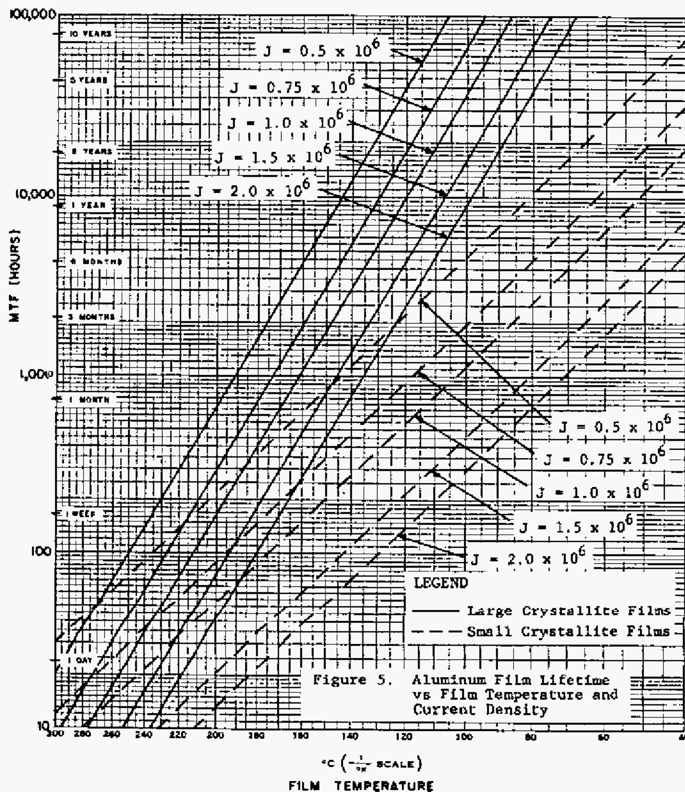

Figure 5. Aluminum Film Lifetime vs Film Temperature and Current Density

Large Crystallite Aluminum Films With A Glass Overcoat

A further increase in activation energy for mass transport should be obtained by the elimination of surface diffusion which is a dominating factor for thin films possessing a high surface-to-volume ratio. By the reduction of both grain boundary and surface diffusion it was predicted that the activation energy should approach that for self-diffusion of aluminum through the crystal lattice of 1.4 eV.

Large crystallite aluminum films were prepared with an overcoat of silica glass deposited by the vapor plating technique to a thickness of 7,000 Å in an attempt to reduce surface diffusion. These aluminum films were 12,200 Å thick and possessed a width of 1.46 mils. The current density for the cells varied from 0.46 to 0.908 × 10^6 A/cm^2 and the mean-time-to-failure ranged from 395 to a predicted 15,000 hours. This experiment is still in progress with three of the six cells exhibiting greater than 50 percent failures at this time (2500 hours).

Figure 6 presents this data where the predicted mean-time-to-failure was obtained for those cells exhibiting few failures by the use

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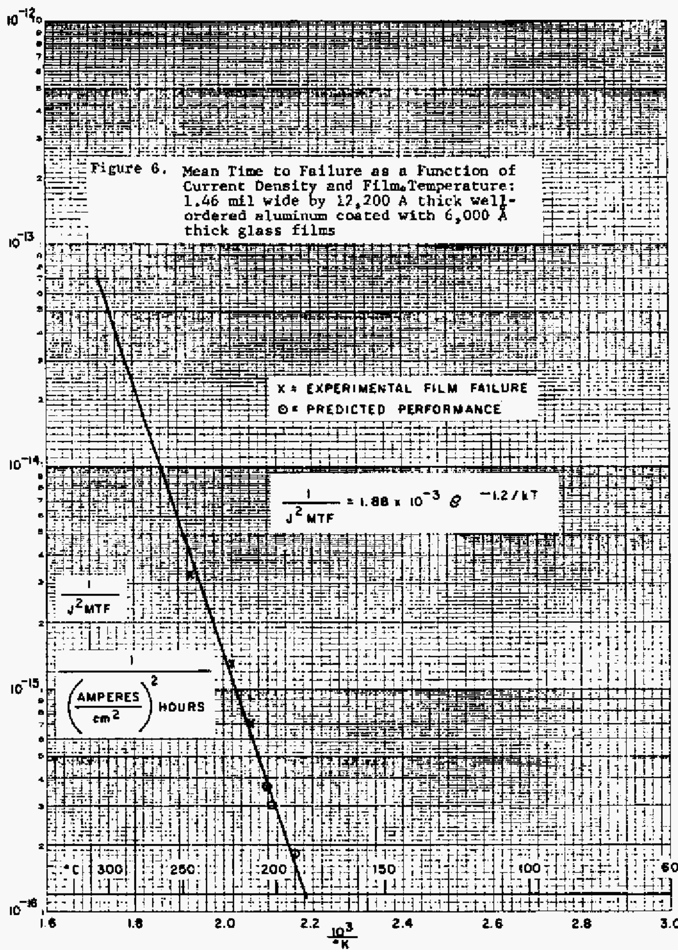

of the Poisson distribution. The formula relating current density and film temperature to the mean-time-to-failure for well ordered glassed aluminum films is

$$\frac{1}{J^2\,MTF} = 1.88 \times 10^{-3} e^{-(1.2/kT)}$$

CONCLUSIONS

The mean-time-to-failure for aluminum conductor stripes stressed at high current densities and elevated temperature can be expressed as:

$$\frac{1}{J^2 MTF} = Ae^{-(\phi/kT)}$$

or

$$MTF = \frac{1}{A}\frac{1}{J^2}e^{(\phi/kT)}$$

where
- MTF = mean time to failure in hours.
- J = current density in amperes per square centimeter
- k = 8.62×10^{-5} eV/atom/°K
- T = film temperature in degrees Kelvin
- A = constant
- ϕ = activation energy in electron volts.

The activation energy for this failure mode has been determined for highly polycrystalline and well ordered large crystalline aluminum films as well as large crystalline aluminum films covered with glass. It appears to be identical with that for the lattice self-diffusion of aluminum in aluminum modified by factors involving both surface diffusion and grain boundary diffusion of aluminum in aluminum. These latter two factors can become important in films formed by the condensation of aluminum vapor.

The value of the constant (A) is expected to be a function of conductor line width and line thickness. Experimental data is being gathered which will enable these geometric factors to be included in the formulas and will be reported in the future.

Large grained well ordered films exhibit values of $\phi = 0.84$ eV and $A = 5.18 \times 10^{-6}$ (for 6,000 Å thick × 0.6 mils wide films). Highly polycrystalline poorly ordered films show $\phi = 0.48$ eV and $A = 2.28 \times 10^{-9}$ (for 7,000 Å thick x 0.5 mils wide films). Well ordered aluminum films overcoated with a glass film to reduce both grain boundary and surface diffusion effects exhibit an activation energy for this failure mode of 1.2 eV approaching the anticipated limit of 1.4 eV which is the activation energy for lattice self-diffusion of aluminum. The value for the constant (A) in this case is 1.88×10^{-3} for 12,200 Å thick by 1.5 mils wide films.

It has been shown that at 270°C there is little difference in conductor lifetime due to the degree of order of the film. This is due to the lattice diffusion component dominating grain boundary and surface diffusion effects at elevated temperatures. At temperatures below 270°C the degree of order of the film becomes most important. At 70°C film temperature nearly two orders of magnitude improvement in the mean-time-to-failure can be gained through the use of well ordered films.

Due to inaccuracies in film temperature measurement and to the small cell size of these experiments an accurate experimental determination of the power for J cannot be obtained even though the value of J has been varied over a range in excess of 5:1. A statistical analysis of the data however indicates that the exponent of J is definitely not unity and exceeds the value of 2 by only a small amount. At this time the exponent value of 2 for J appears to be valid but further work is required to substantiate this.

APPENDIX

Those readers who are interested in a more rigorous development of Equations 6 and 7 are referred to V. B. Ficks, "On The Mechanism of the Mobility of Ions in Metals," Sov. Physics, Solid State, Vol. 1, No.1, p 14, 1959. Utilizing the free electron model and basic concepts of the kinetic theory an expression is developed for the force between conducting electrons and ions to be

$$F_{ei} = eEn\lambda\sigma$$

where n is the electron density. Replacing E by ρJ and remembering that J = nev or n=J/eV, this equation reduces to

$$F_{ei} = \rho\frac{\lambda}{v}\sigma J^2$$

and is identical to the force component developed in the simple model given above.

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