CURRENT LIMITATIONS OF THIN FILM CONDUCTORS

James R. Black
Motorola Semiconductor Products Sector
5005 E. McDowell Road
Phoenix, AZ 85008
(602) 244-6201

Electromigration in thin film conductors is recognized as a potential wear-out failure mechanism for semiconductor devices. Design guidelines have been established limiting the maximum current densities for aluminum and aluminum alloy conductors. With the development of new lithography and etching techniques enabling the construction of very small conductors and spacings the validity of these guidelines has been questioned. Utilizing known experimental data of the lifetime of Al, Al 2% Si and Al 4% Cu 2% Si conductors new guidelines are presented which define the maximum design current density as a function of the conductor temperature and the conductor current. These maximum current densities established by electromigration considerations are further limited by the product of the thicknesses of the conductor and the underlying dielectric thickness which determine conductor temperature gradients caused by the conductor rise in temperature above that of the substrate. Data are presented for the above metal films on vitreous silica.

Introduction

The electromigration wear-out mechanism of thin film conductors carrying high current densities at elevated temperatures is recognized as a factor which can lead to semiconductor device failure. Guidelines have been established which limit the design maximum current density for aluminum and aluminum alloy film conductors to 2×10^5 and 5×10^5 A/cm^2 respectively[1]. The question has arisen as to the validity of these guidelines. It is the purpose of this paper to evaluate the known electromigration experimental data of Al, Al/Si and Al/Cu/Si thin film conductors in order to establish maximum design current densities as a function of conductor temperature and conductor current. A limit to the maximum current densities set by temperature gradients due to Joule heating of the conductors is also attempted. Finally, the combined current density limits due to electromigration and temperature gradients is presented.

Electromigration Current Density Limits

Figure 1 presents an Arrhenius plot of experimental data obtained at our laboratory for glass passivated Al, Al 2% Si and Al 4% Cu 2% Si thin films. Al and Al 2% Si behave similarly and the data for the silicon alloy has been published previously[2].

Experimentally groups of conductors are stressed at elevated current densities and temperatures. The time of each device failure due to an open circuit is recorded for each group and these are observed to follow a lognormal distribution. The time required for 50% of the devices in each group to fail is plotted in Figure 1 for the 50% failure line. Experimentally knowing the average lognormal failure distribution (σ) to be 0.4 for all of the sample groups stressed at various temperatures and current densities the other failure rate plots (10%, 1%, 0.1% and 0.01%) are then constructed.

The cross sectional area of the conductor (wt) appears in the numerator of the empirical expression because it has been experimentally determined that for conductors whose width is greater than the average metal grain size, the median lifetime T_{50} is a direct function of the conductor cross section. A small void generated by electromigration in a small cross sectional area conductor would be fatal while that same sized void in a larger conductor would not be significant.

The power of the current density (J) was experimentally obtained by plotting the log of the lifetime (50% fail) in hours of groups of identical samples stressed at the same temperature against the log of the current density. The slope of this plot is slightly greater than 2 indicating that the power of J is close to 2.

Since T_x, the time for x percent of the group to fail in hours, is in the denominator of the empirical expression on this plot lifetime increases as one goes down the ordinate.

Since the experimental data follows an Arrhenius relationship one can obtain an expression for the empirical factor to be:

$$\frac{wt}{J^2 T_x} = P \exp\left(-\phi/k^{o}K\right) \qquad (1)$$

where:
w = conductor film emitter in cm
t = conductor film thickness in cm
J = current density (amperes/cm^2)
T_x = time for x percent failures (hours)
P = a constant dependent upon percent fail and film composition
ϕ = activation energy in electron volts
k = Boltzman's constant (8.62×10^{-5} eV/°K)
°K = film absolute temperature.

It should be emphasized that the power of J and the activation energies obtained by the above described experiment relate only to the failure of a thin film conductor of the given composition which fail due to an open circuit by electromigration processes. At the operating temperatures of semicondcutor device thin film conductors the atom flux due to electromigration takes place mainly down grain boundaries. Also, theoretically[3] and experimentally[4] (using methods where the conducting film is not failing) it has been shown that the power of J is unity for mass transport by electromigration. In a failing conductor, however, the current density, the temperature and the volume resistivity of the failing member of the conductor are not constant. There is no intent to imply that the activation energies and the power of J obtained with experimental methods utilizing failing conductors apply to the mass transport of aluminum down grain boundaries. The activation energies and the power of J obtained by measuring the T_{50} lifetime of groups of conductors are simply those relating to conductor lifetime which is of interest here.

The data presented in Figure 1 and the discussion which follows relate only to conductor films which are wider than the average grain size of the aluminum film from which they are constructed. As the conductor's width is reduced and approaches or becomes less than the average grain size, the structure begins to "bamboo," that is, most of the grain boundaries become normal to the electron flow and the relationships shown in Figure 1 no longer apply.

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metal fatigue due to the disparity in thermal expansion coefficients between the conductor and substrate could promote conductor failure under pulsed conditions. It is of interest, therefore, to calculate the rise in temperature of a thin film aluminum or aluminum alloy conductor over that of a silicon substrate as a function of current density when the conductor is supported by a thin vitreous silicon dioxide film.

The definition of thermal conductivity of a material χ is:

$$\chi = \frac{\frac{\text{watts}}{\text{cm}^2}}{\frac{^{\text{o}}\text{C}}{\text{cm}}} = \frac{\text{watts}}{\text{cm}\ ^{\text{o}}\text{C}} \qquad (10)$$

The temperature rise of a thin metal film of thickness t_m, width w_m and length l_m on a dielectric film of thickness t_d and thermal conductivity χ is:

$$\Delta T = \frac{\text{watts}\ t_d}{l_m w_m\ \chi} \qquad (11)$$

where watts is the power dissipated in the conductor. This power dissipated in the conducting film can be expressed as:

$$\text{watts} = \rho J^2\ l_m w_m t_m \qquad (12)$$

where ρ = volume reistivity of the metal (ohm-cm)
J = current density in the metal film (A/cm^2)

Substituting equation (12) into equation (11)

$$\Delta T = \frac{\rho J^2\ t_m t_d}{\chi} \qquad (13)$$

where both ρ and χ are temperature dependent. It is of interest to note that the temperature rise of the conductor over that of the substrate is independent of the lateral geometry of the conductor. The temperature rise is a direct function of the metal volume resistivity, the metal thickness, the dielectric thickness and the square of the current density. The temperature rise also varies inversely with the thermal conductivity of the dielectric. As the conductor thickness increases (for a constant current density) the wattage dissipated in the conductor increases. Also as the dielectric thickness increases the dielectric thermal resistance increases. Thus the product of the metal and dielectric thicknesses is an important factor in determining the conductor temperature.

Equation (13) ignores thermal flux spreading at the edges of the metal film in the dielectric and should be quite accurate until the width of the metal film approaches or becomes less than the thickness of the dielectric film. The error is conservative since the conductor would be cooler than calculated.

The volume resistivity of pure bulk Al as a function of temperature is[5]:

$$\rho = 2.42 \times 10^{-6}\ (1 + 4.752 \times 10^{-3}{}^{\circ}\text{C}) \qquad (14)$$

The National Bureau of Standards has published a graph of the thermal conductivity of high purity fused quartz as a function of temperature.[6] An equation of a curve which closely fits this data is:

$$\chi = 2 \times 10^{-8}(^{\circ}\text{C})^2 + 3.84 \times 10^{-6}(^{\circ}\text{C}) + 1.43 \times 10^{-2} \qquad (15)$$

Substituting equations (14) and (15) into equation (13) and assuming that the dielectric temperature was the average temperature of the substrate and the metal, this equation was solved iteratively to determine the Al metal film temperature as a function of the metal current density and the product of the thicknesses of the metal and the dielectric film with the silicon temperature being 20°C. This is presented in Figure 6 where it is seen that the temperature increases rapidly with current density.

A 1 µm thick aluminum conductor on a 1 µm thick vitreous silicon dioxide film would use the 1 x 10^{-8} cm^2 $t_m t_d$ curve which doesn't appreciably rise in temperature at 5 x 10^5 A/cm^2 but at a current density of 5 x 10^6 A/cm^2 will reach 80°C. At a current density of 1 x 10^7 A/cm^2 the film would reach temperature of 500°C. Note that the melting temperature of pure aluminum is 660°C and aluminum in contact with silicon will form a eutectic which melts at 570°C. This same low melting eutectic is formed by the chemical reaction of Al and SiO$_2$ above 450°C. Even if a metal was available which is very resistant to electromigration there appears to be a temperature barrier which limits the maximum current density to the high 10^6 A/cm^2 or low 10^7 A/cm$_2$ range.

The thermal conductivities of other useful dielectric films for the semiconductor industry must be better understood. It is believed that the thermal conductivity of polyimide films is less than that of SiO^2. The thermal conductivities of the various silicon nitride are of interest. Also, the use of multilayered metal and dielectric film structures will further complicate the analysis.

At the present time the effect of the magnitude of the rise in temperature of the conductor above the substrate temperature on electromigration conductor failure is not known. In an ohmic contact region where the conductor film typically rises up over a 1 µm thick SiO$_2$ film a temperature rise of 1°C would introduce a temperature gradient of 1 x 10^4°C/cm. If the electron flow is in the direction of the + thermal gradient mass will be removed from the high temperature region faster than mass is brought to that region from the cooler conductor. This introduces a site for early electromigration failure. Since film temperature varies as the square of the current density it was believed conservative, using equation (13), to calculate the current density which would raise the aluminum conductor film temperature one degree centigrade over that of the substrate as a function of film temperature and the product of the thicknesses of the aluminum metal and the SiO$_2$ dielectric. These data are presented in Figure 7. The current density decreases slowly with temperature since the volume resistivity of the aluminum increases with temperature at a faster rate than does the thermal conductivity of the SiO$_2$.

For the case of 1 µm thick metal on 1 µm thick SiO$_2$ the maximum current density which limits the conductor temperature rise to 1°C varies with temperature between 6 x 10^5 and 7 x 10^5 A/cm^2. A temperature rise of one half degree centigrade would limit the maximum current density for such a film to about 3 x 10^5 A/cm^2.

Since the volume resistivities of Al, Al 2% Si and Al 4% Cu 2% Si are quite similar. The temperature rises calculated for Al were assumed to apply for the alloys.

Combined Electromigration and Temperature Gradient J_{max} Limits

Using the 1°C temperature rise data to determine

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the maximum current densities limited by Joule heating, the associated product of the Al and SiO_2 thicknesses were plotted along with the minimum conductor cross sectional area limited by electromigration characteristics for Al and Al 2% Si as presented earlier in Figure 2. This is shown in Figure 8. For 1 μm thick Al on 1 μm thick SiO_2 the region on this graph above and to the right of the $t_m t_d = 1 \times 10^{-8}$ cm^2 dashed line is forbidden. Only by making the conductor thickness or the dielectric thickness thinner (or both) can one enter this region without generating an excessive conductor temperature rise.

The maximum current density limited by electromigration considerations for Al and Al 2% Si alloy conductors as presented in Figure 3 is shown in Figure 9 with limits imposed by temperature rise of 1°C established by the product of the thicknesses of the metal and dielectric. The region of this plot above the metal and dielectric thickness product are inaccessible due to excessive temperature rise.

Graphs similar to those of Figures 8 and 9 are presented in Figures 10 and 11 for Al 4% Cu 2% Si on SiO_2. From Figure 10 it is seen that for 1 μm thick metal on 1 μm thick SiO_2 a conductor carrying 1 A current cannot be narrower than 150 μm (6 mils) no matter how cool the substrate is. Figure 11 shows that the maximum current density for the above described film is limited to 6×10^5 A/cm^2 by the film temperature rise due to Joule heating.

Conclusions

1. Contrary to the present maximum current density design guidelines which establish a fixed maximum current density for Al and Al alloy conductors, it has been shown that the maximum design current density is a variable being a function of conductor temperature and the conductor current.

2. From present electromigration data the maximum design current density and the minimum conductor cross sectional area for Al, Al 2% Si and Al 4% Cu 2% Si film conductors has been presented as a function of conductor current and conductor temperature to provide 0.01% failures in 1×10^5 hours operational d.c. life. These data apply to conductors whose width exceed the metal grain size.

3. The maximum design current densities and the minimum design conductor cross sectional areas are limited by the product of conductor and dielectric thicknesses due to temperature gradients in the conductor or the temperature rise of the conductor. Design curves have been presented for the conductor temperature rise over the substrate being limited to 1°C.

4. The maximum current densities and minimum conductor cross sectional areas for conductors carrying very small currents are severely limited due to their very small sizes which are sensitive to the formation of very small voids.

5. The thermal conductivities of useful dielectric films such as polyimide and the various types of Si_3N_4 as a function of temperature should be better characterized.

6. The sensitivity of conductor life to temperature gradients during electromigration stress should be better understood.

7. Multilayered conductor structures will have more severe limits than the single layer structure presented here.

Acknowledgment

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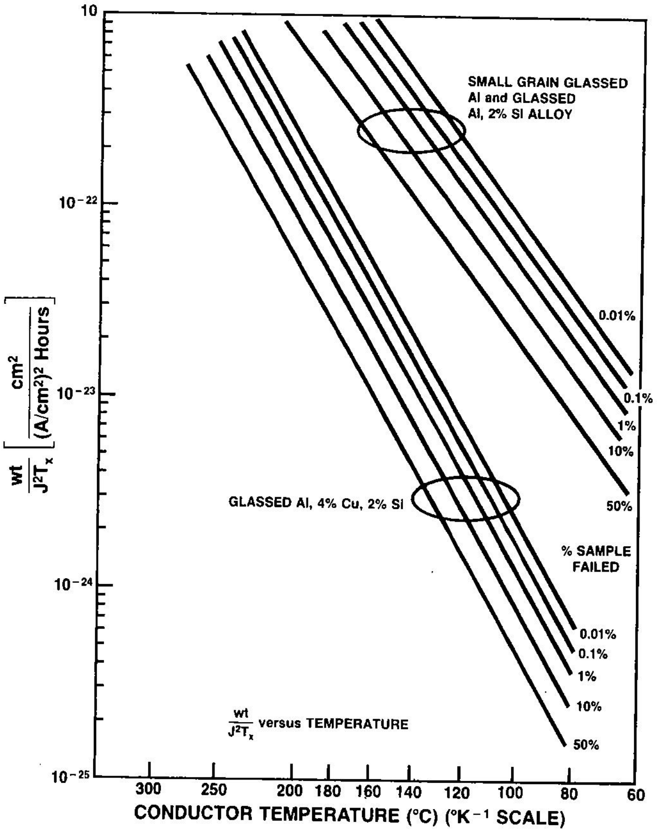

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FIGURE 1

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MINIMUM CONDUCTOR CROSS SECTIONAL AREA FOR GLASSED Al AND Al 2% Si FILM CONDUCTORS

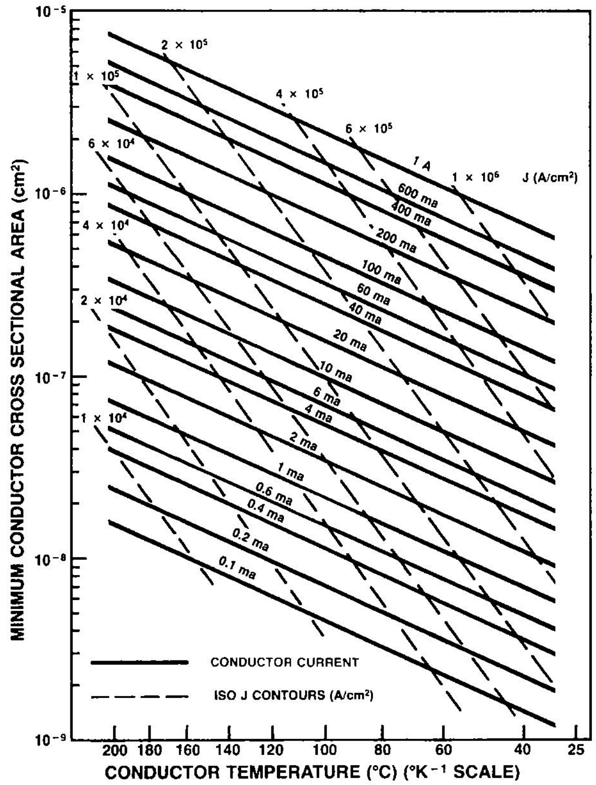

FIGURE 2

MINIMUM CONDUCTOR CROSS SECTIONAL AREA FOR GLASSED Al 4% Cu 2% Si FILM CONDUCTORS

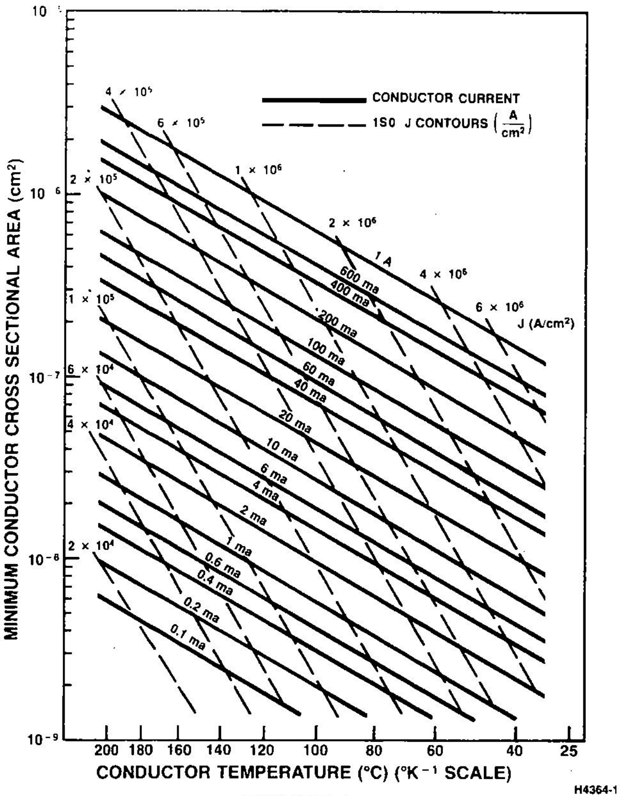

FIGURE 4

MAXIMUM CURRENT DENSITY FOR GLASSED Al or Al 2% Si FILM CONDUCTORS

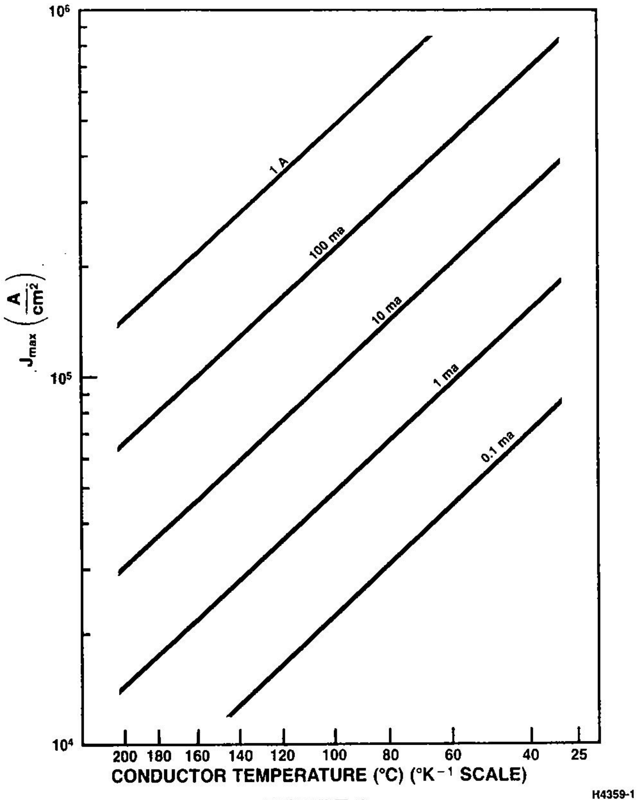

FIGURE 3

MAXIMUM CURRENT DENSITY TO PROVIDE 0.01% FAILURES IN 10^5 HOURS FOR Al 4% Cu 2% Si GLASSED FILM CONDUCTORS AS A FUNCTION OF CONDUCTOR CURRENT AND TEMPERATURE

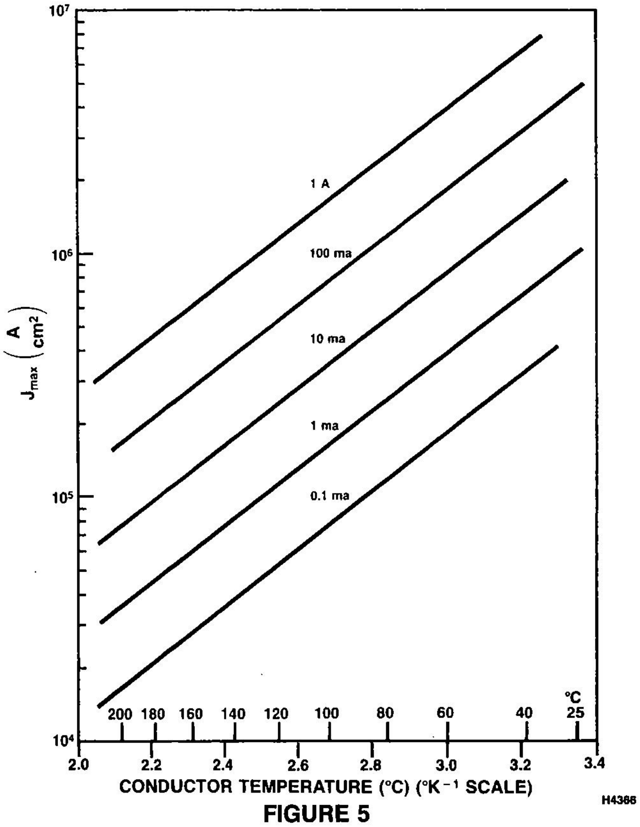

FIGURE 5

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Al FILM TEMPERATURE versus CURRENT DENSITY AND THE PRODUCT OF THE Al AND SiO_2 THICKNESSES. TEMPERATURE OF SUBSTRATE = 20°C.

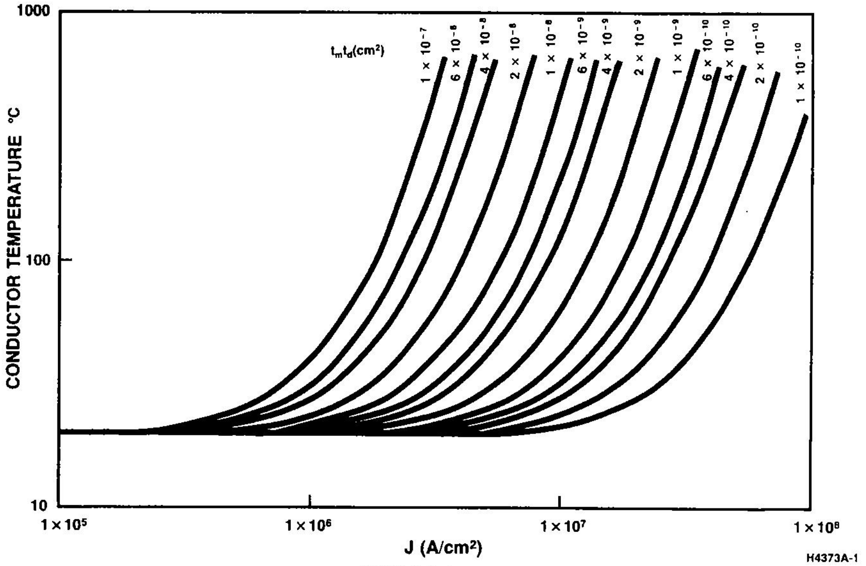

FIGURE 6

J versus TEMPERATURE AND THE PRODUCT OF THE THICKNESS OF THE METAL AND THE SiO_2 FOR 1°C CONDUCTOR TEMPERATURE RISE

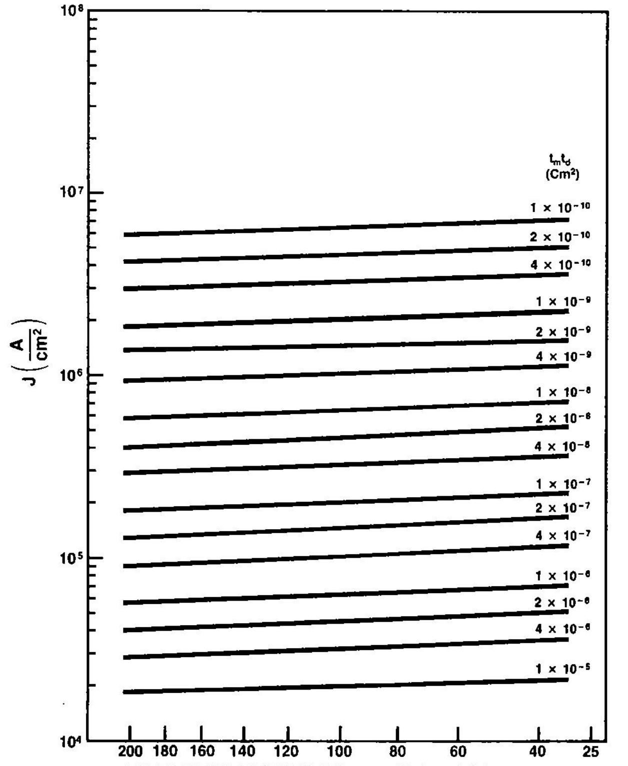

FIGURE 7

MINIMUM CONDUCTOR CROSS SECTIONAL AREA versus CURRENT WITH METAL AND SiO_2 THICKNESS LIMITATION FOR Al and Al 2% Si

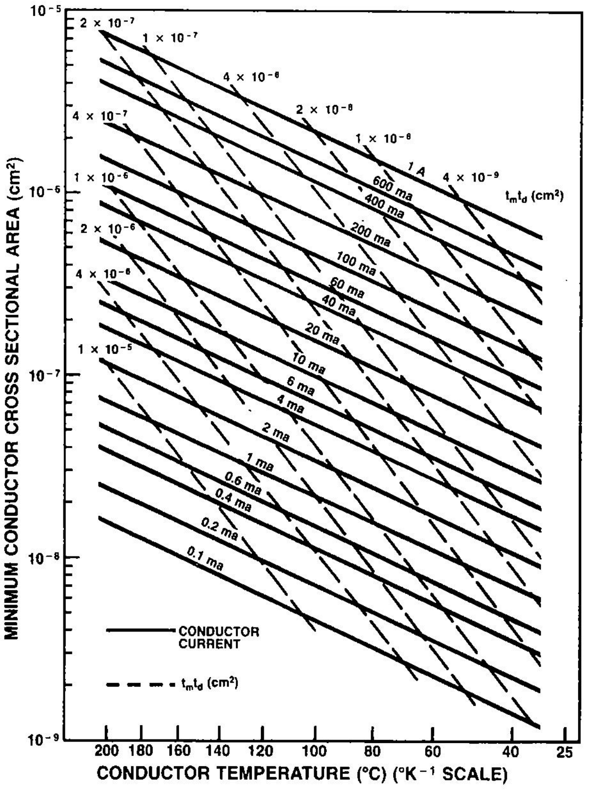

FIGURE 8

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MAXIMUM J FOR GLASSED Al AND Al 2% Si FILM CONDUCTORS WITH METAL AND SiO_2 FILM THICKNESS LIMITS

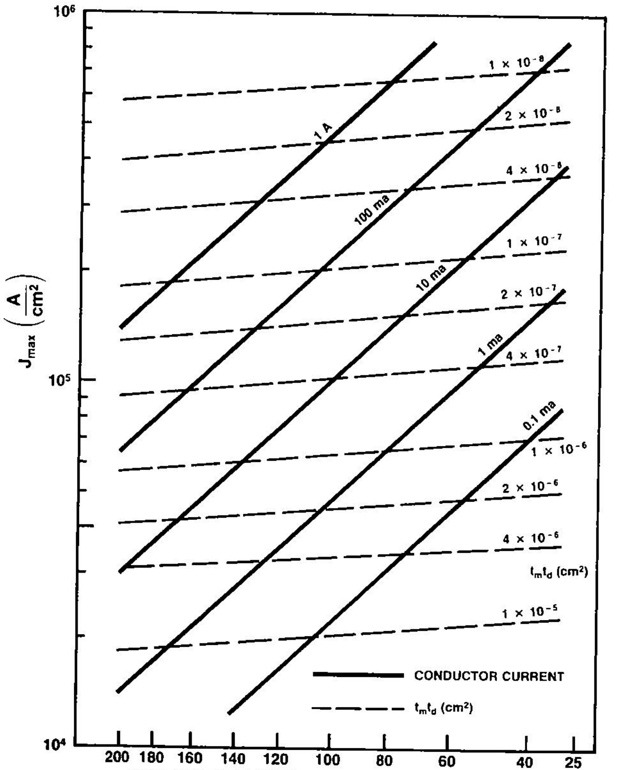

FIGURE 9

MINIMUM CONDUCTOR CROSS SECTIONAL AREA FOR GLASSED Al 4% Cu 2% Si FILM CONDUCTORS WITH SiO_2 AND METAL THICKNESS LIMITS

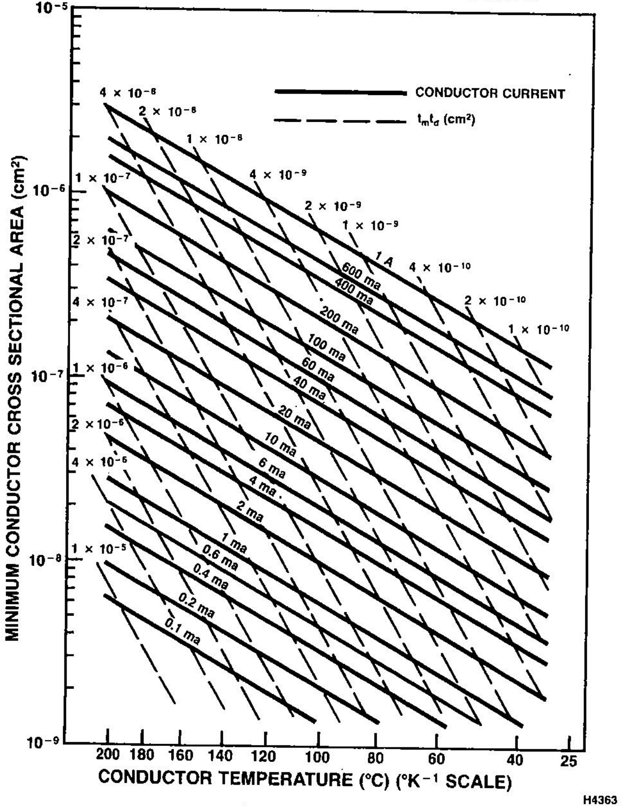

FIGURE 10

MAXIMUM CURRENT DENSITY FOR PASSIVATED Al 4% Cu 2% Si FILM CONDUCTORS ON SiO_2 versus CONDUCTOR CURRENT AND TEMPERATURE WITH METAL AND SiO_2 THICKNESS LIMITS

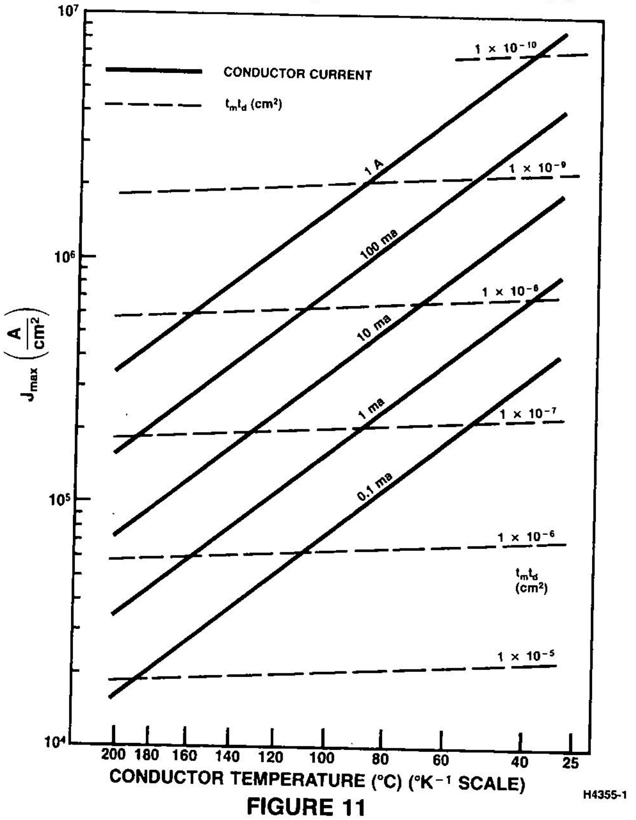

FIGURE 11

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