ELECTROMIGRATION IN THIN-FILM PHOTOVOLTAIC MODULE METALLIZATION SYSTEMS *

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ABSTRACT

Electromigration as a possible thin-film module failure mechanism is investigated using several specially made, fully-aluminized thin film photovoltaic (TF-PV) modules. The effect of electromigration, as determined experimentally by measuring increases in electrical resistance across scribe lines, can be expressed as a product of a damage function, which correlates degradation rate with operating conditions such as current density and temperature, and a susceptibility function, which is defined by module design parameters, particularly aluminum purity and the configuration of the intercell region.

Experimental measurements and derived acceleration factors suggest that open-circuit failure resulting from electromigration should not be a serious problem in present state-of-the-art TF-PV modules. Nevertheless, significant intercell resistance increases can result from long term electromigration exposure, especially in future high-efficiency modules. The problem can be alleviated, however, by appropriate metallization applications and/or proper design of the intercell region.

INTRODUCTION

Electromigration, a recognized reliability problem in thin-film aluminum microcircuits [1-7], is characterized by the current-induced transport of metallization in the direction of the electron flow. It is responsible for the creation of voids, leading to open-circuits, and of hillocks and whiskers, leading to short circuits. It usually occurs above threshold current densities of about $5x10^5$ amp/cm^2.

A common type of amorphous-silicon (a-Si) PV module features successive thin-film layers, on glass, of transparent conductive oxide (TCO), amorphous silicon, and aluminum metallization, the latter applied by vapor deposition or sputtering to a nominal thickness of from 0.2 μm to 0.5 μm. Adjacent cells are electrically interconnected by selective overlapping of the thin-film layers such that the back metallization of one cell has a low resistance path to the front surface TCO of an adjacent cell. This conductive path can be implemented by scribing away the a-Si layer, thus allowing the deposited rear metallization to directly contact the transparent front conductor, or by using a third metal--a "bridging conductor"--to bridge the gap between the rear metallization and the front conductor, Fig. 1.

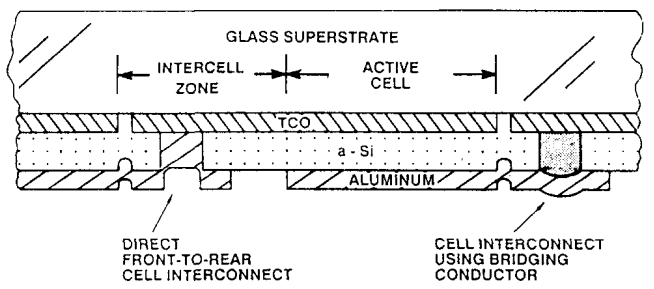

Fig. 1. Schematic Cross-Section of a-Si Cell

In present state-of-the-art designs, a 1' x 1' PV module operates at an average current of 1 ampere. The corresponding current density through a 0.4 μm metallization is about $8x10^2$ amp/cm^2--well below the $5x10^5$ amp/cm^2 electromigration threshold. However, very high levels of local current density can exist in certain sensitive areas within the intercell zone, such as at the laser scribe lines. Along the step-like edges of the scribe lines, and along the sides of the bridging conductor, the thin-film aluminum metallization may be considerably thinner than the nominal thickness of the metallization that exists over the active cell, or baseline, regions away from the intercell zones. Scanning Electron Microscope (SEM) photomicrographs of the step-like laser scribe edges, Fig. 2, reveal large granular surfaces, while the bridging conductor (silver-glass frit), Fig. 3, consists of highly irregular surface of micro-spheres. Metallization covering these critical areas is

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Fig. 2. SEM Photomicrograph: Step-like Change in Metallization along Laser Scribe Edge

Fig. 3. SEM Photomicrograph of Bridging Conductor

highly non-uniform between peaks and depressions, forming voids and very thin metallization regions along the conductive path. Optical photographs of back-lighted pristine samples show two lines of transmitted light coincident with the edges of the contact scribe, Figure 4, indicating voids in the metallization along the sides of the bridging conductor and, similarly, along the step-like edges of the laser scribe lines when no bridging conductor is used.

Local current density along the scribe line edges can easily exceed the electromigration threshold. The critical question, then, is whether the electromigration degradation rate is sufficiently high to fail the module within its intended design life? The objective of the present investigation is to address this question. The approach involves developing a realistic criterion for determining test acceleration factors and then testing representative samples under accelerated conditions in order to determine whether in fact electromigration should be regarded as a TF-PV module reliability issue.

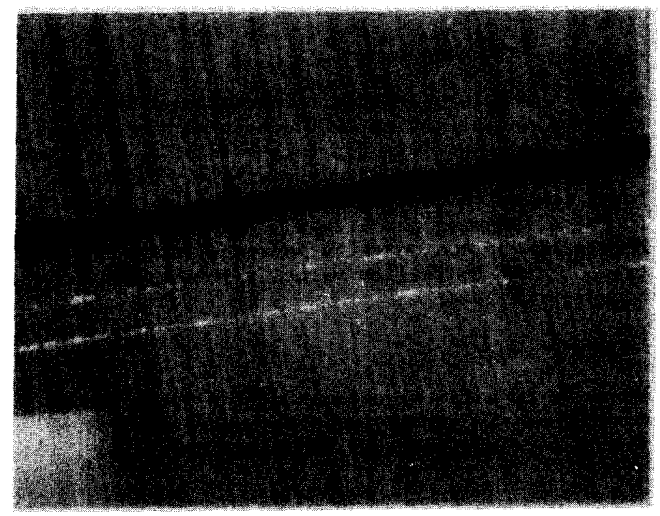

Fig. 4. Optical Photograph: Voids Along Edge of Laser Scribe Line

ELECTROMIGRATION PHYSICS

Electromigration in thin-film aluminum is essentially an activated, biased diffusion process wherein the applied electric field forces acting upon metallization atoms (activated ions) are overwhelmed by the charge carrier (electrons) momentum transfer forces, with the result that aluminum atoms tend to migrate toward the positive terminal in the circuit. This view of electromigration is summarized in the following model [3-5]:

$$F = (Z^{*}e)E \quad (1)$$

$$u = D(Z^{*}e)/fkT, \; D = D_o \exp(-Q/kT) \quad (2)$$

where

- F = net force exerted on migrating ion.
- e = electronic charge, 1.6×10^{-19} coulomb.
- E = impressed electric field.
- u = mobility, i.e., velocity per unit electric field.
- D = self diffusion coefficient, cm^2/sec.
- Q = activation energy for diffusion, eV/mole.
- f = metallurgical factor
- k = Boltzmann constant, 8.62×10^{-5} eV/mole-^{o}K.
- T = temperature, ^{o}K.

Z* is the effective charge number, a dimensionless parameter that takes into account the above-mentioned two-force mechanism; it has been measured to be an exponential function of current density j [8]:

$$Z^{*} = Z_o \, j^m \quad (3)$$

Since the migration velocity v = uE and the current density $j = E/\rho$, where ρ is the conductor resistivity, the relationship among ion migration velocity, mobility and current density can be expressed as follows:

$$v = u\rho j \quad (4)$$

At TF-PV module operating temperatures, the aluminum metallization diffuses primarily along grain boundaries [9]; for this case, f = 1. Flux divergences at grain boundary triple points and nodes create voids in the metallization, increasing the metallization porosity p. The rate of metal depletion, or the porosity increase rate, is proportional to the ion velocity v at grain boundary [3,10]:

$$dp/dt = C_n\ v \quad (5)$$

where C_n is a factor accounting for grain boundary conditions--in particular, the number density of flux divergence centers. Combining Eqns. (2) - (5) gives

$$dp/dt = [C_n\ (D_o\ Z_o\ e/k)\ \rho\ ][j^{m+1}\exp(-Q/kT)(1/T)] \quad (6)$$

ELECTROMIGRATION IN TF-PV MODULES

Experimental Program

A program was undertaken at JPL to test for electromigration in fully metallized TF-PV modules obtained from several module manufacturers. Mfgr. A modules feature bridging conductors in the intercell zone; Mfgr. B and C modules do not. Mfgr. B provided two types of modules, the major difference being the purity of the aluminum metallization. For the purpose of accelerated testing, the modules were cut into 1" x 12" strips across which 1 to 4 amperes of DC current were impressed. Because the responsive areas are highly localized, direct observation and measurement are extremely difficult; thus several experimental techniques have been employed in order to observe and assess the effects. SEM observations and optical photographs of pristine samples have been employed to identify regions susceptible to electromigration damage, Figs. 2 - 4. Infrared thermography has been employed to locate scribe lines most likely to exhibit electromigration phenomena and to monitor temperature levels and gradients. Thermal nodal analysis was performed to model the intercell current density and joule heating conditions. In addition, sample temperature/resistance histories provided some data on runaway electromigration failure. Finally, quantitative data on electromigration were provided by periodic four-point probe resistance measurements across the scribe lines obtained using microprobes under an optical microscope.

Local Current Concentration and Resistance Levels

As stated in the introduction, the critical areas for electromigration in TF-PV modules are at regions within the intercell zone, such as along the laser scribe edges, where the metallization coating is considerably thinner than elsewhere and where (presumably) as-manufactured voids, Fig. 4, exist. The problem arises from attempting to coherently cover a surface having a 1 μm step with a 0.2 - 0.5 μm conformal coating. Because of area constriction along the scribe line edges, the local current density, j, can be significantly higher than the nominal current density, j_o, in the baseline region:

$$j = b\ j_o \quad (7)$$

At a test current level below 1 ampere, the samples are essentially isothermal at near-ambient temperature. At a 3-amp current level, infra-red thermography, using an Inframetrics Model 525 imaging camera, reveals the sample scribe line regions to run 10°C to 15°C hotter than the baseline regions (around 70°C), Fig. 5, reflecting a high local resistance at the scribe line edges. The wide variations of temperature levels observed also suggest that there are significant differences in the porosity characteristics along the various scribe line edges. The level of initial porosity can be characterized by a ratio R_o/R_i, where R_i is the local resistance of a pristine sample, and R_o is the would-be resistance level at zero porosity.

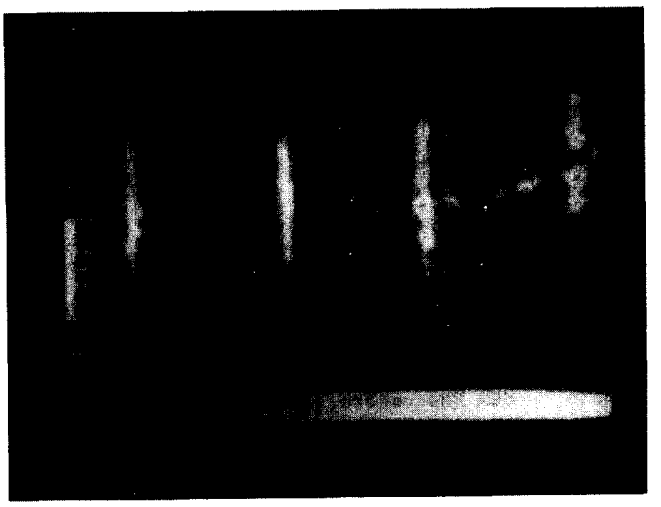

Fig. 5. IR Thermograph: Temperature Profile of Electromigration Specimen

As shown in Fig. 4 the initial porosity at the step-edges can be 50% or higher.

A 40-node mathematical model was constructed using Mini-Mitas Thermal Analyzer [11] and exercised to simulate the observed sample temperature levels and profiles. The current density concentration ratio, b, along the scribe line edges was assessed to be in the range 100 to 500 in order to produce the joule heating required to match the actual observed temperatures. This level of current concentration is sufficient to exceed electromigration threshold levels.

Four-point probe measurement techniques, routinely performed under an optical microscope, were employed to obtain resistance variations across the scribe lines and at the baseline metallization.

Although the scribe line edges (about 2 μm to 4 μm) constitute no more than 4% of the total scribe line width, the scribe line edge resistance, R, is higher, by a factor of 2 to 10, than that of the rest of the scribe line. This suggests that for pristine scribe lines the local metallization thickness is not only significantly less than that at the baseline, but also varies widely among scribe lines. These measurements confirm the IR thermography observation and verify the assessment of a 100 to 500 factor increase of scribe line current density over baseline levels.

Resistance Variation and Damage Function

When local current density is above the electromigration threshold, the corresponding local resistance R at the scribe line edge can be correlated to porosity development:

$$R/R_i = (R_o/R_i)/(1-p) \quad (8)$$

The rate of local resistance change is

$$d(R/R_i)/dt = [(R/R_i)^2/(R_o/R_i)]\ dp/dt \quad (9)$$

The modelling Eqns. (6), (7), and (9) suggest that electromigration in TF-PV modules is affected by factors that can be grouped into two categories--module design parameters, as embodied in a module susceptibility function S, and module operating conditions, as embodied in a damage function Φ; Eqn. (9), integrated, then yields

$$R_i/R = 1 - S\ \Phi\ t \quad (10)$$

$$S = C_n\ (D_o\ Z_o\ e/k)\ b^{m+1}\ \rho\ (R_i/R_o)$$

$$\Phi = j_o^{m+1}\ \exp(-Q/kT)/T$$

The module susceptibility function, S, is determined by material properties (resistivity, diffusivity, and metallurgical factors such as, for example, grain boundary conditions) and by manufacturing design features (intercell configuration, metallization deposition techniques, metallization thickness, and possible overcoatings). For a particular module, the effect of operating conditions is characterized by the damage function, Φ, which is determined by the operating conditions (temperature and current density).

In general, test samples may be subjected to irregular intervals of testing at different levels of current density and temperature. The damage function then consists of a superposition of the individual damage functions:

$$R_i/R = 1 - S \sum_i j_{o,i}^{m+1}/T_i\ \exp(-Q/kT_i)\ \Delta t_i \quad (11)$$

If the temperature level and current density remain somewhat constant during the test period, the time-degradation relationship can be expressed, with $n = m+1$, as follows:

$$t = 1/S\ [1-(R_i/R)]\ T\ j_o^{-n}\ \exp[Q/kT] \quad (12)$$

The time to failure, t_F, can be determined by specifying a smallest tolerable value for the initial-to-final scribe line resistance ratio R_i/R. Then Eqn. (12) becomes

$$t_F = 1/S'\ T\ j_o^{-n}\ \exp[Q/kT] \quad (13)$$

Eqn. (13) is the form of the empirical equation relating median-time-to-failure, MTF, and current density, j, employed in VLSI circuit reliability studies [3,5]: $MTF = BTj^{-n}\exp[Q/kT]$. The exponent n is 1 for isothermal electromigration, and is 3 when temperature variations become significant [5]. Most experimentists suggest a level of n between 2 and 3 [5,7]. However, over the years, experimentalists have reported values for n ranging from 1 to 10 for different ranges of current density [10]. In the present study, the value of $n = 3$ is suggested. This is consistent with the choice $m = 2$, giving a parabolic dependency between Z^* and j: $Z^* = Z_o\ j^2$.

Accelerated Test Results

Field operating conditions differ significantly from laboratory testing environments. Usually both the reference current density j_o and the temperature T utilized in the laboratory are much higher than module field values. This, of course, impresses a more severe damage dosage than that for which the module is designed. An acceleration factor can be defined as the ratio of exposure times that produce identical damage in two different environments. Table 1 lists damage functions and acceleration factors, assuming $n = 3$ and $Q = 0.55$ eV/mole [12], for several test environments. As an example, the electromigration damage produced by one hour of testing at $4x10^4$ amp/cm^2 and 125°C is equivalent to about 11,000 hours of testing at $1x10^4$ amp/cm^2 and 24°C.

Table 1

Damage Function and Acceleration Factors

Test Conditions				
I, amp/inch of sample width	1	2	3	4
j_o, amp/cm^2	$1x10^4$	$2x10^4$	$3x10^4$	$4x10^4$
T, °C	24	35	82	125
Damage function, T	1.6	26	1190	17,540
Acceleration Factor	1	16.5	756	11,140

With the damage function established, the effect of electromigration on a module can be related to the susceptibility function S. Of the four sample types tested, only the high purity aluminized sample of Mfgr. B failed, i.e., open-circuited. These samples were subjected to various current levels in the range of 1 - 4 amps and their scribe line resistances were periodically measured using needle probes under an optical microscope. The data are shown in Fig. 6 with R_i/R plotted against

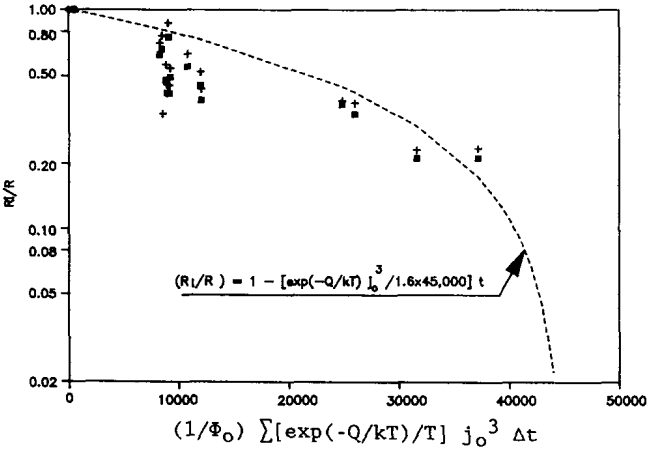

Fig. 6. Scribe Line Resistance Variation vs Damage Function

a normalized accumulated damage function $\sum 1/\Phi_o$ $j_o^3/T \exp(-Q/kT)\ \Delta t$, where Φ_o is the damage function for $I_g = 1$ amp/inch of sample width ($j_o = 1 \times 10^4$ amp/cm^2) and $T = 24^oC$: $\Phi_o = 1.6$ (see Table 1). The analytical function that best fits the data is $R_i/R = 1 - S\ \Phi_o\ t$, with $S = 1/(1.6 \times 45{,}000)$. From the results in Table 1, the expected mean lifetime for these high purity aluminum metallized modules of Mfgr. B will be 45,000 hours for $j_o = 1 \times 10^4$ amp/cm^2, $T = 24^oC$; about 56 hrs for $j_o = 3 \times 10^4$ amp/cm^2, $T = 82^oC$; and about 4 hours for $j_o = 4 \times 10^4$ amp/cm^2, $T = 125^oC$.

DISCUSSION

The fact that all samples except those metallized with high purity aluminum survived more than 2000 hours of testing at $j_o = 3 \times 10^4$ amp/cm^2 and $T = 82^oC$ suggests that purer metallizations and smaller grain sizes adversely affect the module susceptibility function S. The reason generally advanced for this is that smaller grain size metallization has a greater density of flux divergency centers (void nucleating nodes). Alloying to achieve larger grain sizes or fewer flux divergency centers tends to reduce electromigration effects, but introduces galvanic couples that enhance susceptibility to electrochemical corrosion.

Because initial resistance varies significantly from scribe line to scribe line within the same module, it is anticipated that a large variation in susceptibility function exists among scribe lines. This was clearly demonstrated by variations in measured scribe line resistance values. While some intercell zones displayed open-circuit failures or significant increases in local resistance, other intercell zones exhibited very little change in resistance.

Dielectric overcoatings were observed to reduce electromigration effects, presumably by eliminating surface components of electromigration. However, this result is preliminary and requires additional investigation to establish quantitative correlations.

CONCLUDING REMARKS

Is electromigration a reliability issue for TF-PV modules? Based on the results of the present investigation, the answer appears to be no. Although module failures due to electromigration have been observed in the laboratory, post-experiment analyses indicate that the acceleration factors associated with these experiment amount to lifetimes far in excess of 20 years nominal operation.

We do not expect that open-circuit failure due to electromigration in TF-PV modules will become a serious reliability problem in the future. However, intercell resistance increases may become an issue for long term interaction between electromigration degradation and corrosion. A future high-efficiency, thin film module having a 1' wide, 0.4 μm thick metallization and carrying a 6-amp current can be expected to generate a nominal current density, j_o, as high as 5×10^3 amp/cm^2. If the module design is of the type that repeatedly failed under the accelerated testing of this investigation, and is operated at a nominal temperature of 50^oC, the mean failure time to electromigration-induced open-circuiting is expected to be 24 years, assuming 8 hour daily operation. The intercell resistance due to electromigration alone will double within 12 years.

Should it become necessary, there are ways to reduce the likelihood of electromigration damage. One design approach to minimize electromigration in TF-PV modules is to increase the metallization thickness (at the expense of cost). Additional factors under the designer's control include metallization purity and grain size (which may affect corrosion resistance), and the use of non-conductive, perhaps passivating, coatings.

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