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GEOMETRIC CHARACTERIZATION OF ELECTROMIGRATION VOIDS (A STATISTICAL ANALYSIS OF ELECTROMIGRATION VOIDS)

SUNY Cortland

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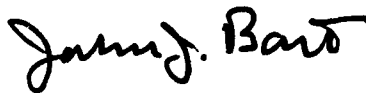
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13. ABSTRACT (Maximum 200 words) The areas, perimeters, lengths, and widths of 998 electromigration induced voids on 38 test stripes have been measured by SEM and digital image analysis. Virtually all of the voids occurred along the passivation-conductor interface on the side of the stripe. A plot of the number of voids on each stripe versus time to failure does not extrapolate to zero at zero time to failure, which suggests there are a certain number of active sites predisposed to voiding.				
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INTRODUCTION

Since the first observations of voids in microelectronic conductors, the models used to describe and predict void growth and subsequent line failures have grown increasingly refined and complex [1-10]. Models being developed include more and more factors, from the macroscopic, such as the effect of passivation thermal constants on the temperature gradients in the metal [9], to the microscopic, such as the effect of grain boundary lattice angles on the mobility of impurities [1]. These models are approaching the point where they can predict statistically not just the overall lifetimes of the lines, but more microscopic information such as the distribution of the void sizes along the line. The measurements described here provide a starting point for testing the predictive powers of these models by providing experimental data for comparison at these more microscopic levels. Obviously, comparison with data from stripes of different dimensions, materials, microstructure, or stress treatment is necessary to determine the general applicability of each model.

EXPERIMENTAL

The 38 test stripes used for this analysis are a subset of the test stripes fabricated and lifetime tested by previous authors; stripe preparation and lifetime test procedures are discussed in detail elsewhere [11]. The test stripes are sputtered Al + 1%Si meander lines 1650 μ long, 3.4 μ wide, 0.8 μ thick, and passivated with 0.4 μ of SiO₂. The stripes were subjected to a current density of 2×10^6 A/cm² in a 150°C oven until the stripes failed. The present measurements were performed eight years after the original lifetime tests were run -- it is quite possible that some relaxation has taken place.

The individual voids were cataloged and measured using a Cambridge S-120 scanning electron microscope equipped with an ETP-USA Robinson backscattered electron detector model 120-MX. All measurements were made with the passivation layer still in place. Electron microscope images were sent directly to a Bioscan Optimas digital image analysis system. Void areas as small as 0.04 μ^2 could be resolved. For each void, the area and perimeter length were measured, as well as the length and width. Here "length" is used to denote the extent of the void parallel to the

direction of current flow and "width" denotes the extent of the void perpendicular to the current, regardless of the shape of the void.

RESULTS

On the 38 test stripes examined, a total of 998 voids were observed. One of the most striking general observations was that virtually all of the 998 voids occurred along the edge of the stripe. Even those voids which had grown farther across the stripe than they had along the stripe always touched one edge of the stripe. This phenomenon was true for all void sizes. One would expect that any reasonably large void would grow out to the edge even if it was nucleated at the center of the stripe. However, even the small voids were found along the edge. Less than a dozen of the 998 voids did *not* touch the edge of the stripe.

This result suggests that the passivation-conductor interface at the side of the conductor is the primary location for void nucleation. If any significant number of voids nucleated near the center of the stripe one would at least expect to see a number of the smaller voids near the center of the stripe. However, this was not the case. The passivation-conductor interface is expected to be a region of larger thermal gradients. The thermal gradients at the interface may contribute to the tendency for voids to be nucleated there [12].

Measurements were taken of the void areas, perimeters, lengths, and widths. The distributions are shown in Figure 1. All of the distributions are sharply peaked near low values but have a long tail, as seen in the width distribution. The curves have been fit using a log-normal distribution of the form

$$g(x) = \left\{ \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{C(x-A)} \right\} \exp \left\{ -\frac{1}{2C^2} \left[\ln \left(\frac{x-A}{B} \right) \right]^2 \right\}$$

where

$$A = Z_0 - \frac{W\rho}{(\rho^2 - 1)} \quad C = \frac{\ln \rho}{\sqrt{2 \ln 2}} \quad B = \frac{W\rho}{(\rho^2 - 1)} \exp(C^2)$$

W is the width of the distribution, Z_0 is the position of the center of the peak, and ρ is the skew of the distribution [13]. The values of W, Z_0 , and ρ used to fit the distributions are given in Table 1. The fitted curves have been normalized so that the area under the fitted curve is the same as the area under the data.

A log-log plot of the number of voids on each stripe versus the time to failure (TTF) indicates that the number of voids varies roughly as the square root of time. The number of voids versus the square root of the time to failure and the total void area

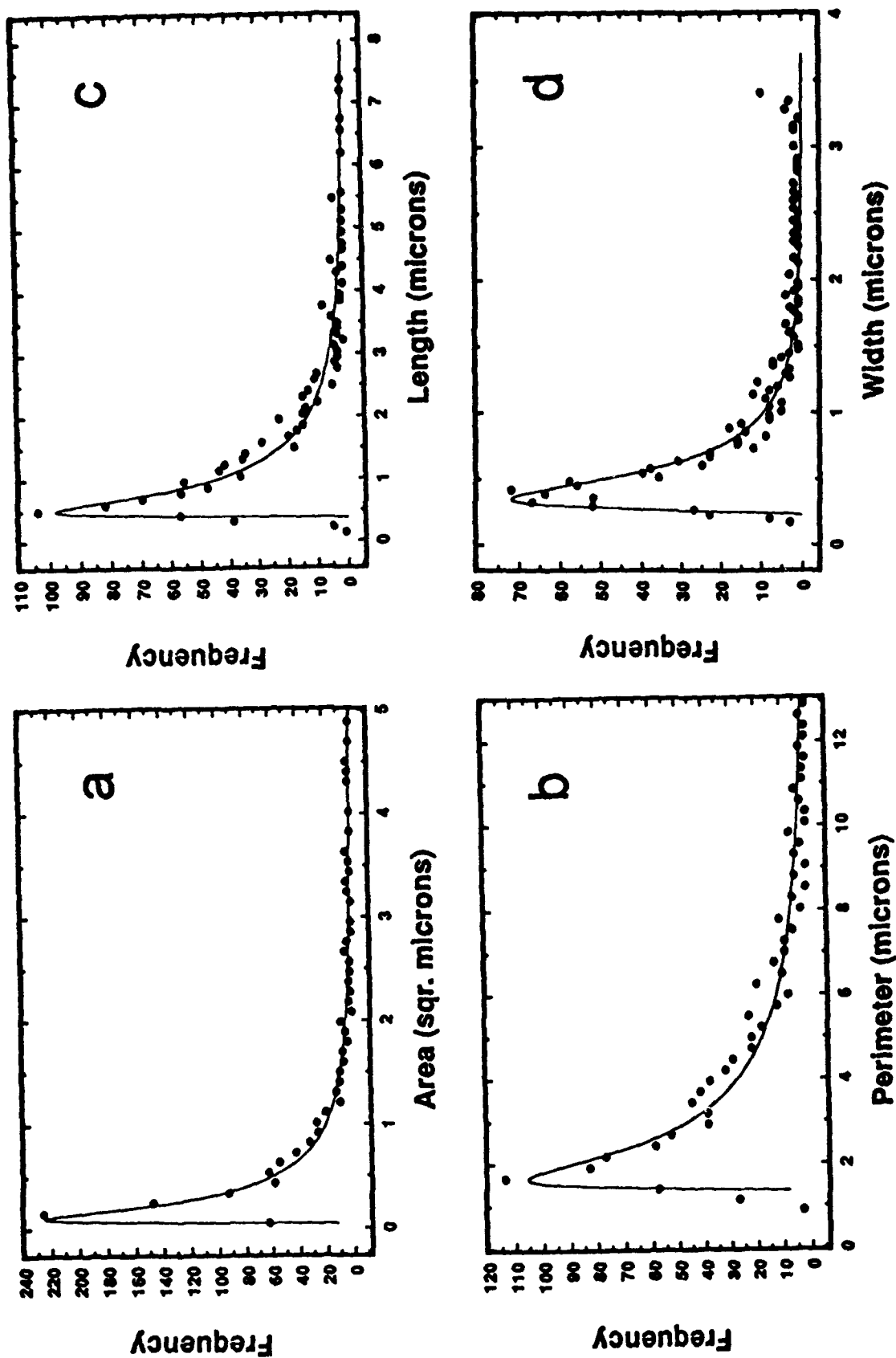


Figure 1. Distributions of void a) area, b) perimeter, c) length, and d) width measurements shown with curve fitted to a log-normal distribution.

Table 1. Parameters used to fit distributions. W is peak width, ρ is the peak skew, and Z_0 is the center of the peak.

MEASUREMENT	W	ρ	Z_0
area	0.24	4.8	0.095
perimeter	1.37	4.7	1.65
length	0.53	4.6	1.65
width	0.32	2.9	0.35

versus the time to failure is shown in Figure 2, each with a least squares fit to the data. The data on Figure 2a represents a subset of the data reported by previous authors [14]. Although there is significant scatter, especially on the plot of total void area, a fairly strong correlation is clear,

as is expected. The linear regression for the number of voids versus the square root of the time to failure has an intercept of less than one and a slope of 10.0 per day^{1/2} with a correlation of 0.76. The linear fit to the total void area versus TTF has an intercept of 6.96 μ^2 and a slope of 1.33 μ^2 /day with a correlation of 0.82.

The relationship between the total void area and the time to failure is less clear. Because the *number* of voids is growing, even assuming a constant growth rate for each void does not lead to a linear relationship between total void area and the time to failure. Further analysis and modelling is underway. Making the simplest (though perhaps not the most physical) assumption of a linear dependence of total void area on time to failure does, none the less, suggest an interesting result: the intercept at zero time to failure is not zero.

This positive y intercept makes sense either if there are a number of voids too small to be resolved or if there are a certain number of active nucleation sites on the stripes - defects of one kind or another -- which are predisposed to voiding. Other voids come about from the usual thermal and mechanical stresses due to current load. The predisposed sites would be in essence voids waiting to happen and would open up under the slightest stress. It is interesting to note that extremely few stress voids were found on the guard stripes, so it is unlikely that there were many (if any) voids on the stripes prior to lifetime testing. To the extent that the zero TTF intercept represents a measure of active nucleation sites, the relationship of total void area to time to failure may provide a mechanism for comparing the number of pre-stress active nucleation sites for different materials or fabrication techniques.

It is also interesting that even with the fairly strong correlations between the number or total area of voids and the time to failure, there is little correlation between the average void size and the TTF, as shown in Figure 3. Here a least squares fit gives a correlation of only 0.45.

Because of the competing influences of thermal gradients, direction of current flow, and grain boundary forces, it is not clear from a theoretical standpoint whether voids will *on average* grow farther parallel to the current than they grow perpendicular to it (as is commonly accepted) or vice versa. The experimental distribution of the ratio of the void lengths (extent parallel to the current) to the void widths (perpendicular to the current) is shown in Figure 4a. The center of the peak is around 1.3, indicating more

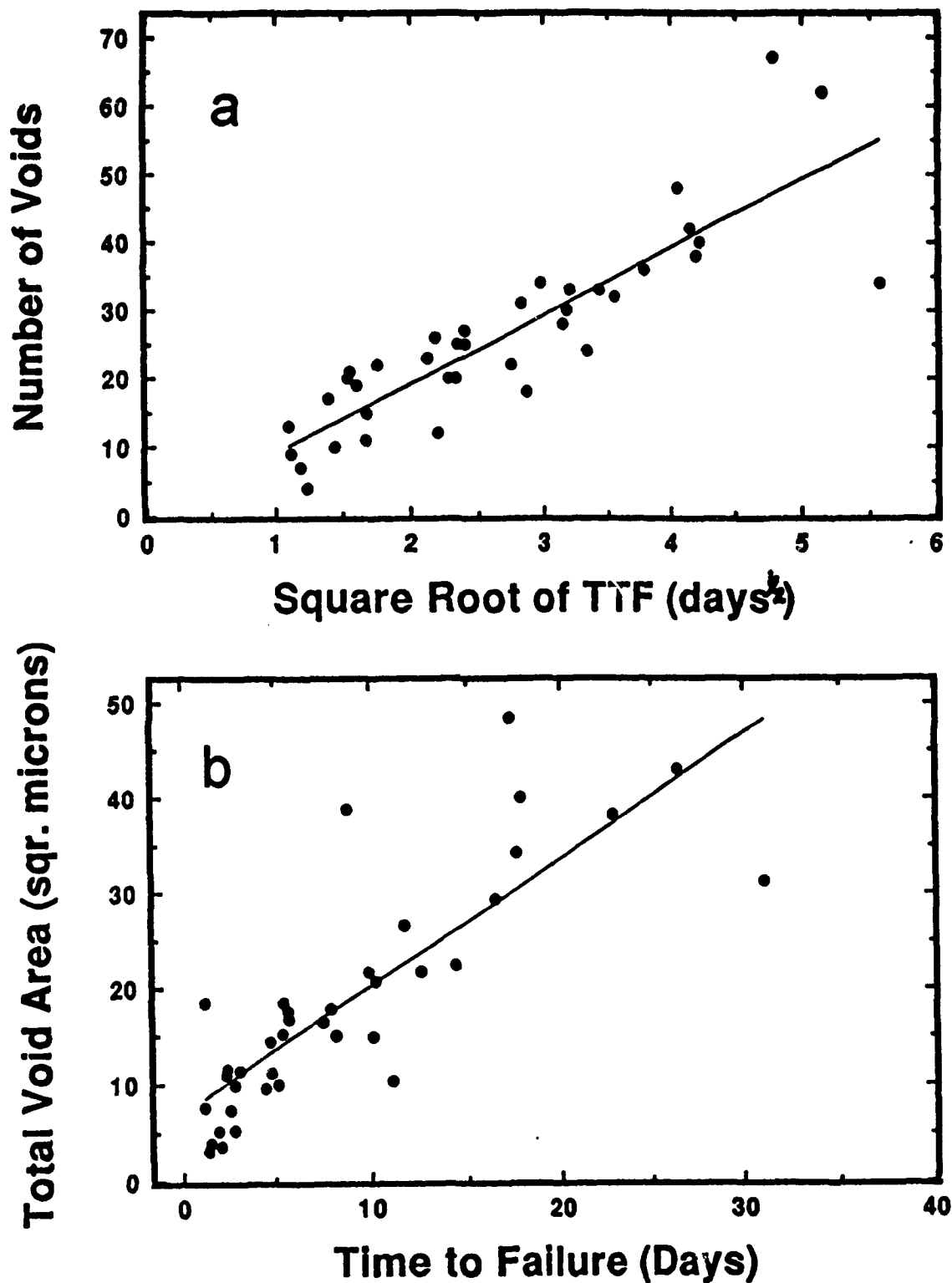


Figure 2. a) The number of voids on each part versus the square root of the time to failure for that part. b) The total void area on each part versus the time to failure for that part.

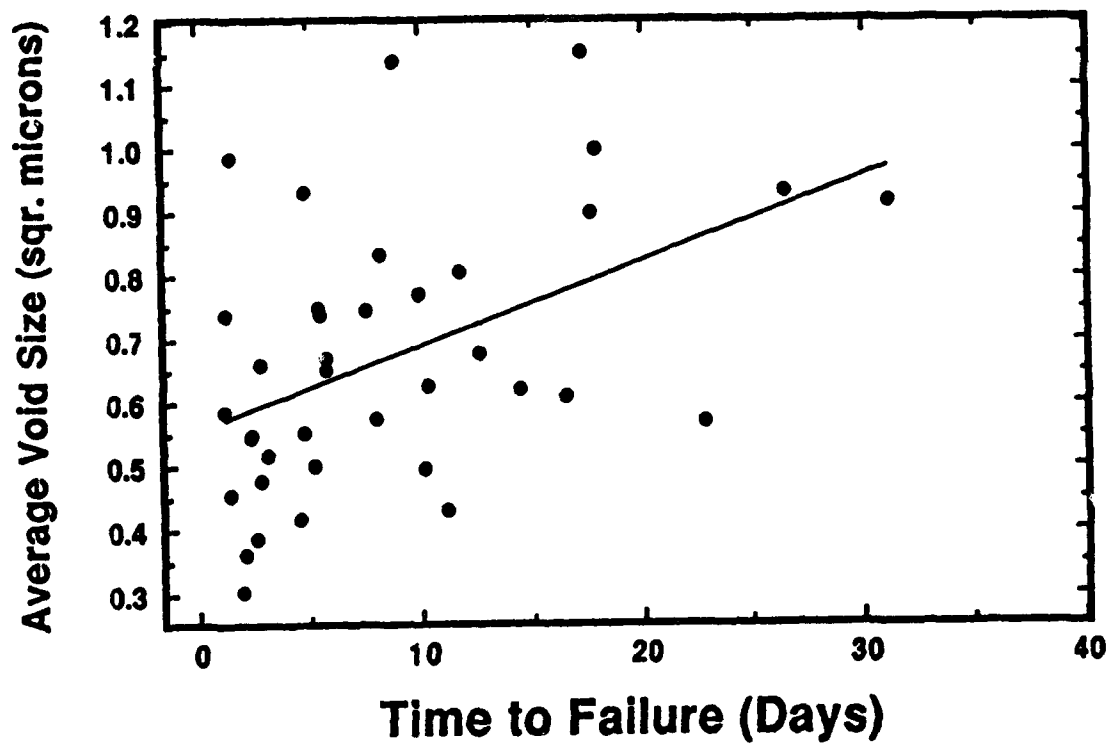


Figure 3. The average void area on each part versus the time to failure.

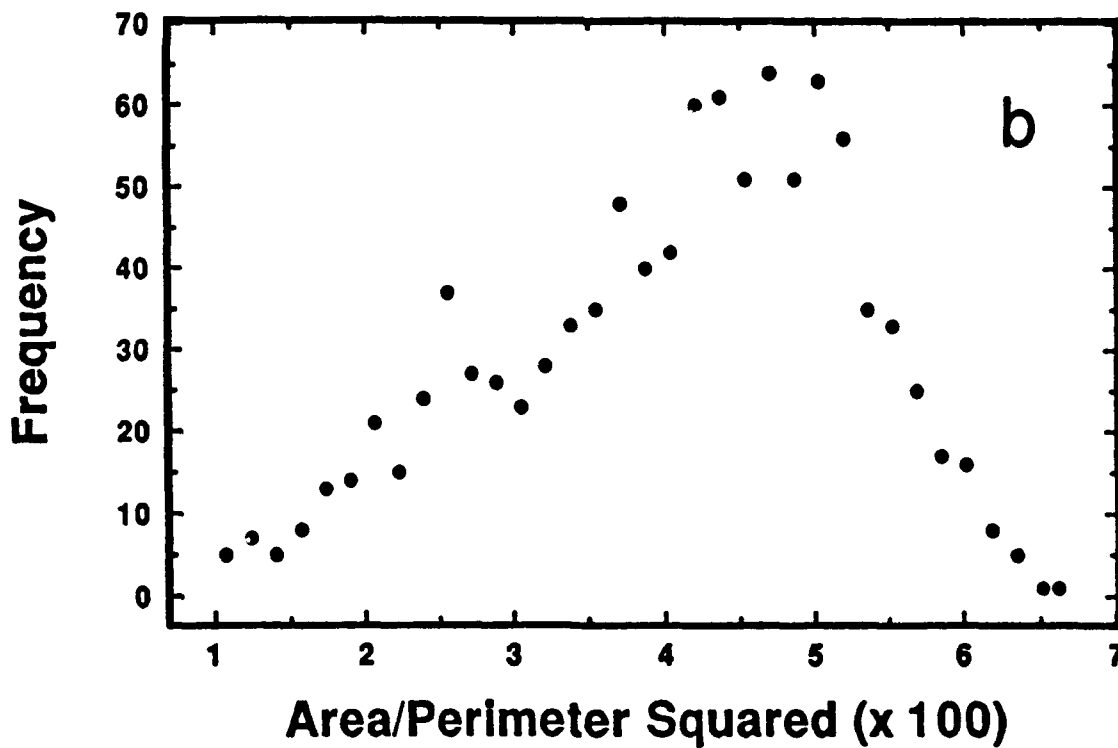
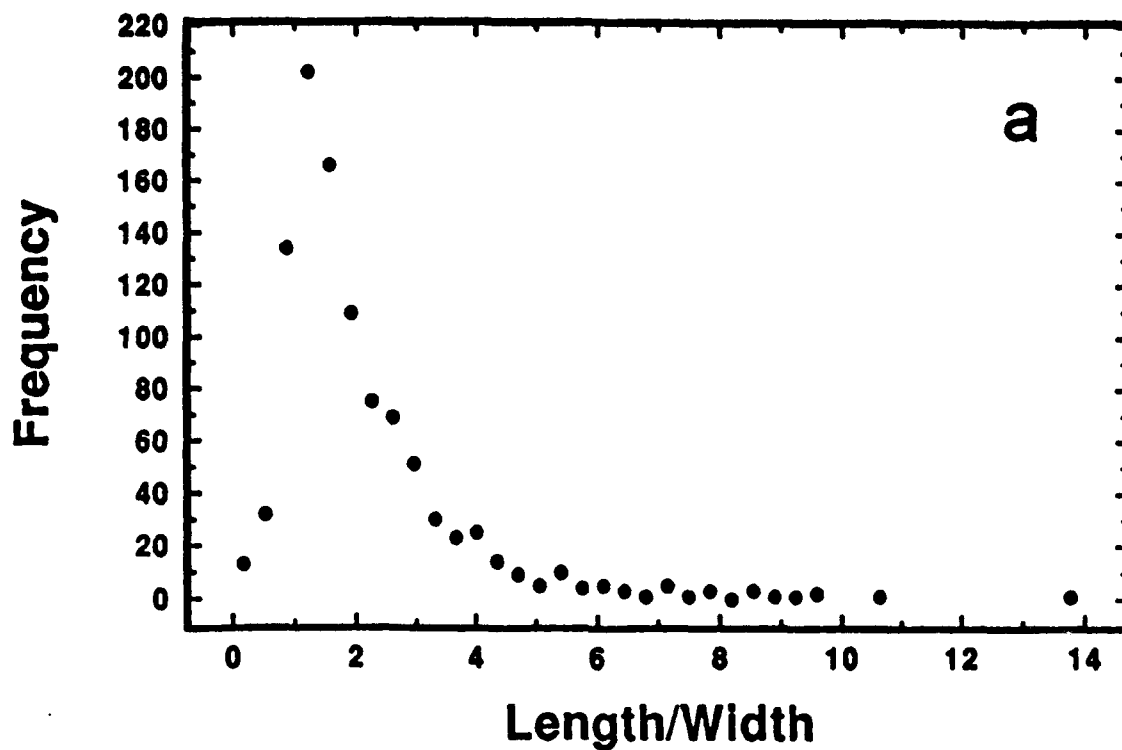


Figure 4. a) The distribution of the ratio between the void lengths and the widths. b) The distribution of the ratio between the void area and the perimeter squared.

growth parallel to the current. The long tail to the right (long and/or narrow voids) may reflect that voids grew together along the edge. This growth pattern was apparently the case for many voids, especially on the longest lived stripes.

Figure 4b shows the distribution of the ratio of the area to the perimeter squared. This dimensionless ratio is an indicator of how narrow (in either direction) or rounded the voids were. For example, a circle has an area to perimeter squared ratio of 0.079. Though the distribution is broad, the peak is around 0.045 or 0.050, similar to the ratio of 0.048 found for an equilateral triangle. Many (but not an overwhelming majority) of the larger voids observed were roughly triangular.

CONCLUSIONS

We find that virtually all of the voids have an edge in common with the passivation-conductor interface at the side of the stripe. This result strongly suggests that this location is the primary nucleation site for void formation. The number of voids on each stripe is found to be proportional to the square root of the time to failure. The total void area does not appear to be directly proportional to the time to failure; assuming a linear correlation between total void area and time to failure there is a sizeable zero TTF offset perhaps implying a number of pre-existing sites predisposed to voiding under potential stress. This result may provide a technique for comparing the pre-stress active nucleation sites of different materials. The voids, on average, are longer than they are wide, as is expected, and the peak of the ratio of the area to the perimeter squared is quite close to the ratio expected for equilateral triangles.

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