The Electrical Resistance Ratio (RR) As A Thin Film Metal Monitor

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ABSTRACT

Data are presented which demonstrate the usefulness of RR, the electrical Resistance Ratio between 298K and 77K, for monitoring the quality of Al-Si metal films. A correlation between RR, electromigration Median-Time-To-Fail (MTTF) and Median-Grain-Radius (MGR) of the metal is shown, using examples of N_2 and H_2O contaminated films.

INTRODUCTION

A key measure of metal quality for integrated circuit interconnects is electromigration performance, which is traditionally monitored by stressing a small number of metal lines at a high current density and temperature, until most of them fail. The failure times are then plotted as a lognormal distribution which, if valid, is uniquely characterized by its mean (or median) and sigma (spread of the data).

The time required to process, assemble and stress electromigration structures to failure is too long for a useful manufacturing monitor. Wafer level stressing is more rapid, taking hours instead of weeks, but the cost of running a significant sample size is high.

We propose here a post-deposition measurement of metal quality, the electrical Resistance Ratio (RR), as an in-line process monitor which correlates well to the electromigration Median-Time-To-Failure (MTTF).

RESISTANCE RATIO

The Resistance Ratio for a thin metal film is here defined as the ratio of the film sheet resistance (or sheet rho) at 298K to the sheet rho at 77K, in liquid nitrogen. This measurement has been used as a monitor of aluminum metal film quality for our VLSI devices since 1984, when it was proposed and implemented by Dr. Paul Flinn of Intel. In 1986, Dr. Tim Maloney of Intel introduced a major improvement when he replaced Dr. Flinn's original linear four point technique requiring a rigid ceramic jig with the much simpler and more accurate Van der Pauw method.

The resistance of a metallic conductor is inversely proportional to the mean free path of the conduction electrons. In the case of a pure, defect-free elemental single crystal material, the mean free path will be determined by phonon scattering of the conduction electrons. This interaction is characterized by a temperature-dependent phonon scattering length. The phonon scattering length in aluminum is approximately 70nm at 298K [1] and 900nm at 77K, as estimated from the temperature dependence of the resistance of pure aluminum [2]. It follows that the RR value for bulk single crystal Al will be 900/70 = 12.6.

In the case of thin polycrystalline Al-1% Si films, the electrical conduction at 77K will be significantly limited by additional scattering processes occurring at grain boundaries, film surfaces and at impurity sites within the conductor [3-6]. Both the film thickness and grain size are on the order of 1 micrometer in typical sputtered Al - 1 wt % Si films, comparable to the phonon scattering length at 77K. Atmospheric species incorporated into the film, in addition to dissolved silicon, will contribute to impurity scattering.

These combined effects will reduce the RR value for sputtered Al-Si films below that predicted for pure bulk material. Experimentally, it is found that RR values for sputtered Al-Si thin films lie in the range 6.0 to 9.5, and that the highest values of RR are obtained by sputtering under conditions of high vacuum integrity and through appropriate control of deposition temperature.

In this paper, we describe three examples which demonstrate the correlation of RR to both electromigration MTTF and the Median-Grain-Radius (MGR) for sputtered thin films of constant thickness. The metal films were deposited using Perkin-Elmer 4400 series sputtering equipment, at a base pressure below 10^{-7} torr, and at ambient temperature (approximately 80C). The substrates were cleaned in a dilute HF solution, rinsed and dried prior to deposition.

MEASUREMENT TECHNIQUES

Resistance Ratio Measurement

The RR of Al-Si and Ti/Al-Si films were measured using a simple Van der Pauw four-probe method [7], shown in Figure 1. Van der Pauw's theorem invoked the theory of complex variables to prove that the sheet resistance of any flat,

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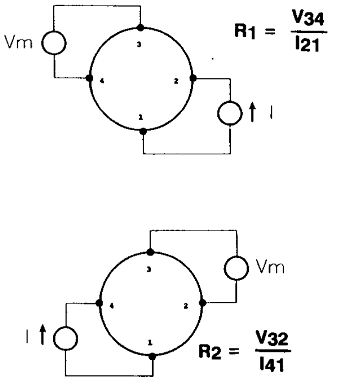

Fig. 1. Four-point Van der Pauw probe scheme for measuring metal film sheet resistance on a test wafer. Current I is forced and voltage Vm is sensed.

uniform thin film of arbitrary shape and simply connected surface (no holes), can be measured by forcing current (I) and sensing voltage (V) in two configurations, using probes on the perimeter of the surface. To implement this, we deposit the metal film on a test wafer, and do the I-V measurements using four spring-loaded minigrabber clips on the edge of the wafer as shown in Figure 1.

The spring-load clips can be thermally cycled and make a firm, reliable connection to the film at both temperatures. Film resistance is measured in the two configurations shown in Figure 1 by using a switch box and a Cambridge Model 510 4-terminal micro-ohmmeter [8]. Forcing current for a typical metal film is 1 Amp (20 milliohm scale, 1 micro-ohm resolution), with V/I typically ranging between 0.5 and 6 milliohms for RR measurements on a 1 micron Al-Si film.

Van der Pauw's theorem generally requires that a transcendental equation be solved for the sheet rho, given R_1 and R_2 as shown in Figure 1. However, it can be shown that as long as R_1 and R_2 are within 10% of each other, a simple average is sufficient and sheet rho $\rho_\square$ is

$$\rho_\square = \pi / \ln 2 \times (R_1+R_2) / 2 \qquad (1)$$

to within 0.1%. It is not difficult to get nearly identical R_1 and R_2 with "eyeball" symmetric placement of the clips on a wafer. Although for RR we need only a quantity proportional to sheet rho, we get the actual sheet rho for free and can easily cross-check this value with the other room temperature metal film monitor data.

Since RR measurements are generally accurate to better than 1%, it is best to correct all room temperature measurement to 25C (298K); such measurements are best made in liquid Fluorinert^{TM} while the bath temperature is accurately measured. The spring-loaded minigrabber probe clips were chosen to avoid problems with freezing Fluorinert during the measurement that follows, at liquid nitrogen temperature.

Grain Size Measurement

The Al-Si grain size distributions were measured by a Reactive-Ion-Etching (RIE) / Scanning-Electron-Microscope (SEM) technique, which has been shown to agree with the standard TEM (Transmission Electron Microscope) method of highlighting the grains [9]. The RIE is used to first remove the passivation layer, and then selectively to remove material from the metal grain boundaries, so that the grains are clearly visible in an SEM. A typical SEM photo after RIE is shown in Figure 2, along with the corresponding TEM photo for comparison. From SEM photographs of the metal film, each grain is traced onto a digitizing table, which is connected to an IBM personal computer with video imaging analysis software (VIAS).

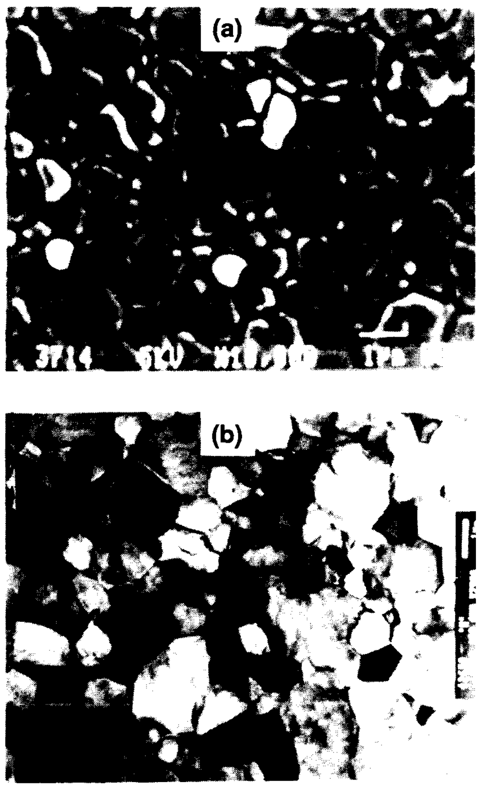

Fig. 2. Al-1% Si grain structure : (a) RIE/SEM and (b) TEM.

RESULTS AND DISCUSSIONS

Variation of Al-Si Metal Quality

Three random engineering lots of material with Al-Si sputter-deposited metal films were used to understand the correlation of Resistance Ratio to electromigration MTTF and median grain size of aluminum microstructure. The Resistance Ratios of these metal films were measured on electromigration test structures after a complete assembly process. The Al-Si microstructure was examined in the bond pads on packaged units using RIE/SEM for grain structure analysis. Each lot underwent identical electromigration stress of $6.6X10^5A/cm^2$ at 175C. The metal line widths were 3.8u.

The stressing was done in an internally designed system, using a Despatch oven with current provided by an SCR power supply. The required current was determined from voltage measurement with a Fluke 8502A multimeter; the data was accumulated with an HP9825B computer.

Figure 3 shows the lognormal plots of electromigration failure times for these three lots. The data show that the sigmas of the failure time distributions were similar, between 0.84 to 1.19, but the MTTFs were different by a factor of 6.2 between the best and the worst lot. The grain radius distributions from these three lots, also lognormal [10], are plotted in Figure 4. The Median Grain Radii ranged from 0.85 to 1.36u, but the sigmas were all about 0.5. In addition, the Resistance Ratios of these three lots measured between 6.5 to 7.9. The most electromigration resistant lot has the largest MGR of Al-Si and the highest RR.

The correlation of electromigration MTTF to Resistance Ratio and Median Grain Radius is shown in Figure 5. We found that the electromigration resistance of the Al-Si metal film increases linearly with both RR and MGR.

The Effect of Nitrogen Contamination on Al-Si Films

The correlation of Resistance Ratio to electromigration performance was further explored by performing experiments at wafer level. In this experiment the metal quality was intentionally varied, by introducing various levels of N_2 (between 18 ppm and 182 ppm) in the sputtering chamber during deposition [11]. RR was measured on the as-deposited metal film. MGR was measured on the bond pads of end-of-process wafers, and MTTF was measured on unpassivated wafers.

Electromigration was performed by placing wafers on a hot chuck at 200C, using HP current supplies controlled by an IBM personal computer. A $2.0x10^6A/cm^2$ constant current density was applied to the test structures with a width of 2.5u. The temperature rise due to joule heating was measured to be 10C. The data show that MTTF ranged from 2.2 to 5.4 hours, with sigmas between 0.43 to 0.56. The MGR varied from 0.42 to 0.94u, and RR was between 7.2 and 8.2. Again, there is a good correlation between Resistance Ratio, median grain radius, and electromigration MTTF as shown in Figure 6. The wafer with the highest nitrogen contamination level has the lowest resistance ratio, the smallest median grain radius, and the worst electromigration performance.

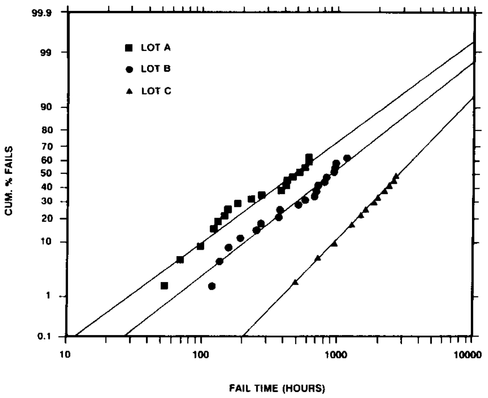

Fig. 3. Metal electromigration failure time distributions for three different lots stressed at 175C and 6.6X 10^5 A/cm^2.

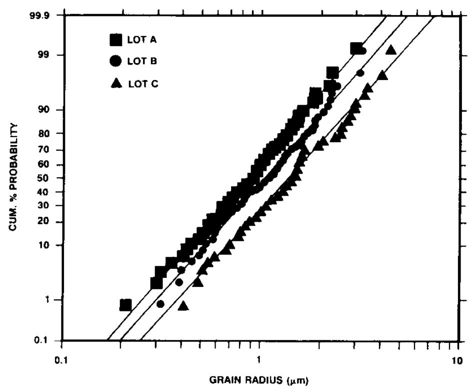

Fig. 4. Cumulative percent probability plots of Al grain radius for the three lots in Fig. 1, measured in the bond pads on packaged units.

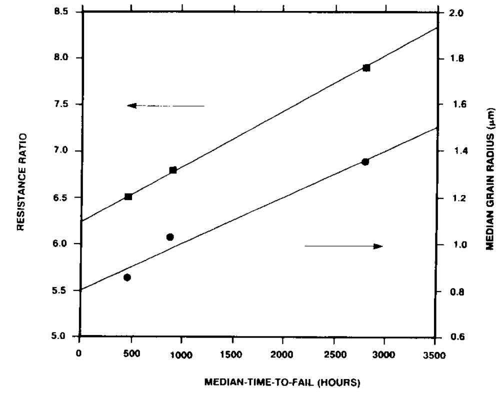

Fig. 5. Correlation of Resistance Ratio (RR) and Median-Grain-Radius (MGR) to Median-Time-To-Fail (MTTF) for the three lots in Fig. 1.

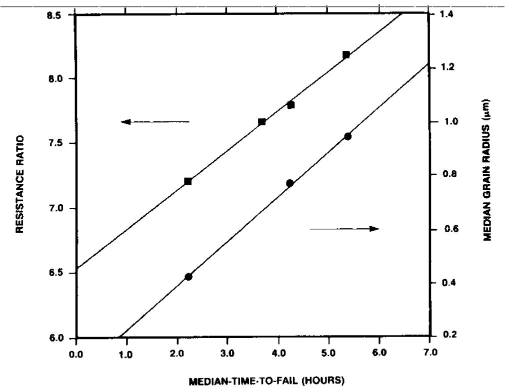

Fig. 6. Correlation of RR and MGR to MTTF for unpassivated N_2 contaminated Al-Si films (increasing contamination from left to right). Rapid failure is due to accelerated stress conditions of 210C and 2.0 X 10^6 A/cm^2.

The Effect of Water Contamination on Ti / Al-Si Films

We also studied the effect of atmospheric contamination on Ti / Al-Si electromigration. The Ti / Al-Si was deposited on two different dielectric films, one of which absorbed moisture from the air (unstable in moist air) prior to metal deposition [12]. The electromigration data were taken at a stress of 6.7X10^5A/cm^2 and 200C. The stable dielectric resulted in an 8X longer MTTF, at about the same sigma, compared to the unstable dielectric. The MGR for the metal over the stable dielectric was 1.6X greater than for the unstable film, also with about the same sigma.

Moreover, the RR of the metal film over the unstable dielectric was only 5.5 as compared to 7.8 for the film over the stable dielectric. Figure 7 shows the correlation between RR, MGR, and MTTF. The results indicate the same trends as described previously: that is, the H_2O contaminated film (pair of points on the left) has a lower RR resulting in a smaller MGR and a shorter MTTF.

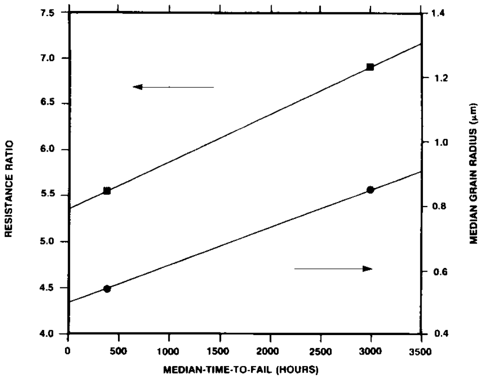

Fig. 7. Correlation of RR and MGR to MTTF for Ti/Al-Si films on stable (MTTF=3000 hrs.) and unstable (MTTF=400 hrs.) dielectric films.

CONCLUSION

We have described the measurement of the Resistance Ratio for metal films, and shown RR data which correlated to both electromigration Median-Time-To-Failure and Median Grain Radius. Several means of varying the grain size were used; for films of constant thickness and (nominal) composition, grain size is the main determinant for RR. However, the RR measurement is simpler than the measurement of Median Grain Radius.

The chart shown in Figure 8 represents RR data taken from sputter-deposited Al-Si monitor wafers over a 40-week perior. Appropriate corrective action is taken when RR falls below 8.0. The high reading (9.5) is probably due to an increase in grain size caused by increased deposition temperature. Low readings can be due to low deposition temperatures, or more likely to chamber atmospheric contamination. Regardless of the cause of the variation, we have found that RR is a rapid and accurate production monitor of metal film quality.

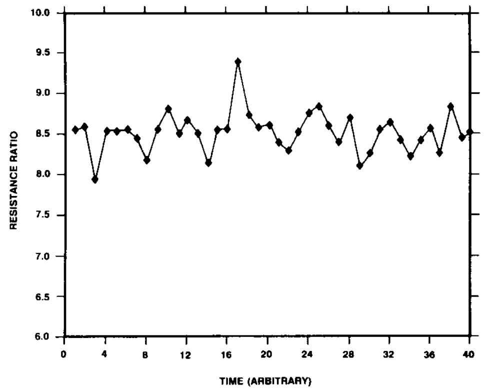

Fig. 8. Typical RR trend chart for one micron as-deposited Al-1% Si Metal film.

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