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Noise measurements in thin-film interconnections: A nondestructive technique to characterize electromigration

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Electromigration in aluminum and aluminum-silicon (1%) resistors was detected by means of a new technique based on the particular features of an ultralow-noise amplifier, which made it possible to evaluate the stochastic resistance fluctuations associated with vacancy generation-recombination processes. The power spectra of these fluctuations display a $1/f^{\gamma}$ behavior with $2 \leqslant \gamma \leqslant 2.6$, in the frequency range 10 mHz–1 Hz, and the analysis of these spectra, recorded at various current densities and temperatures, led to an evaluation of the activation energies characteristic of the process. Scanning electron microscope observation of the damage induced by stressing the resistors at the same current density and temperature as the spectra measurement but for a longer time, showed that what was being observed was the electromigration phenomenon in its early stages.

INTRODUCTION

Aluminum interconnections play a fundamental role in integrated circuit technology, and the evaluation of their ability to resist electromigration (EM) is one of the most important problems from the producer's point of view. The methods traditionally employed to estimate the reliability of interconnections are limited by a drawback which originates from the fact that one can only measure *macroscopic* variations of the strip structure and, hence, one is usually forced to work under accelerated test conditions to obtain a sufficient reduction in the measurement time.[1]

On the other hand, in such conditions the film structure is deeply modified after a short-time interval. For this reason it is difficult to have the certainty that the EM parameters deduced by these methods, activation energy for instance, are simply related to the original structure of the film. There is, in literature, a great dispersion of results regarding the activation energy E_a (Ref. 1) of pure Al films and this dispersion can only be partly attributed to the different structures of the films investigated by the various authors. Structure modifications caused by high-stress conditions are undoubtedly also responsible for data dispersion. A method capable of detecting electromigration when the stress conditions do not cause any appreciable resistance variation could, on the contrary, give information about the parameters which control electromigration in operative conditions of integrated circuits. A method of this kind was proposed by us in a preceding paper[2]; it reveals EM by detecting low-frequency (10 mHz–1 Hz) noise spectra coming from resistance microfluctuations associated with vacancy flux. These spectra display a $1/f^{\gamma}$ behavior with $2 \leqslant \gamma \leqslant 2.6$.[3] Measurements of $1/f$ noise were used to reveal EM or its effects in Al and Al-Si films,[4,5] and, more recently, $1/f^2$ spectra were observed during EM, but in a higher frequency range (1–10 Hz).[6]

After a brief description of the measuring apparatus, the results obtained with Al and Al-Si (1%) resistors using this technique are compared with reisitance variations and with the damage of the films observed by means of a scanning electron microscope (SEM).

EXPERIMENTS

The voltage fluctuations across the current contacts of the resistor to be investigated were amplified by an ultralow-noise amplifier (ULNA) (equivalent input voltage noise power $e_n^2 = 2.5 \times 10^{-15}$, 10^{-16}, 6.3×10^{-18}, 5×10^{-19} V^2/Hz at 10^{-2}, 10^{-1}, 1, 10 Hz, respectively, and a low-frequency limit of 2 mHz) and then processed by a spectrum analyzer (Fig. 1). It was decided to perform the noise measurements across the current contacts after a set of tests proved that the contacts between the wires and the pads of the resistors did not introduce any detectable noise.

A current supply system specifically designed so as to introduce a noise negligible with respect to the one produced by the amplifier was used to set the proper current density.[3] It is made by means of nickel-cadmium batteries and flicker noise free resistors. The current supply system, the amplifier, and the sample under test are contained in a copper box (electric shield) in turn placed in a mu-metal one (magnetic shield).

The resistor temperature was fixed only by the Joule heating and the environmental temperature, to avoid spurious noise from electronic temperature control systems. The measurement started when the resistor reached its thermal

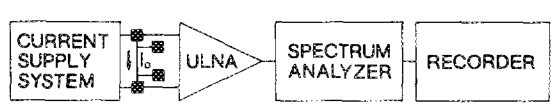

FIG. 1. Scheme of the measuring system.

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equilibrium, the temperature being measured by the resistor itself once its resistance-temperature characteristic was known.

The low-frequency (10 mHz–1 Hz) voltage power spectra were measured at various current density (and consequently temperature) values for Al (R1) and Al-Si (1%) (R2) resistors, deposited by means of an rf sputtering process onto oxidized silicon substrates. The resistor cross section was $16.8\,\mu m^2$ ($14\,\mu m$ width and $1.2\,\mu m$ thickness). The average resistance between the voltage contacts at $T = 23\,°C$ and the average temperature coefficient were 2.7 Ω, $4.1\times10^{-3}\,°C^{-1}$ and 3.1 Ω $4.0\times10^{-3}\,°C^{-1}$ for the R1 and R2 series, respectively. The surface of the film was free, that is, there was no passivating layer either for R1 or R2. The current density and temperature ranges explored were $1.8\times10^6 \leqslant j \leqslant 2.4\times10^6$ A/cm^2, $340 \leqslant T \leqslant 410$ K for R1 and $1.3\times10^6 \leqslant j \leqslant 2.25\times10^6$ A/cm^2, $320 \leqslant T \leqslant 400$ K for R2. The surface morphology of an Al nonstressed sample is shown in Fig. 2, which was taken after Ar ion beam sputtering in order to make the grain texture of the film evident.

Each measurement of an EM noise spectrum required about 4 h. Then the resistor was subjected to the same conditions (current density and temperature) as the noise test for 26 h. Thus, the whole stress duration was 30 h. The results obtained from noise measurements are summarized in Figs. 3 and 4, which show the plots on $\ln S_F$ (20 mHz) versus the reciprocal absolute temperature $1/T$.

$S_F(f)$ is defined by means of the relationship

$$S_F(f) = S_R(f)T/(\rho j), \tag{1}$$

where f is the frequency and $S_R(f) = S_V(f)/I_0^2$ the power spectrum of the resistance fluctuations, $S_V(f)$ being the voltage noise power spectrum across the current contacts and I_0 the constant current flowing through the resistor. As far as the dependence of $S_R(f)$ on f is concerned it was observed that γ assumes a value very close to 2 in the observed frequency range when the stress conditions are such that the microstructure of the films is not deeply modified in a time interval comparable with the noise measurement time; that is, both the percentage resistance variation and the damage of the film are undetectable after a stress period of this duration. Besides, in these conditions the spectra are quasi-stationary; in other words, the power spectral density and its dependence on f do not change after many consecutive noise measurements.

As is well known, the vacancy flux induced by the current density is given[7] by

$$J_V = NeZ^*\rho j D_0 \exp(-E_a/kT)/(kT), \tag{2}$$

where N is the atom density, eZ^* is the effective ion charge, ρ is the film resistivity, j is the current density, k is the Boltzmann constant, and T the absolute temperature. $D_0 \exp(-E_a/kT)$ is the atom diffusion coefficient and E_a the activation energy. In a previous work it has been shown that by making the hypothesis

$$S_R(f_0) = BJ_v, \tag{3}$$

where f_0 may be any value in the observed frequency range (when $\gamma = 2$) and B is a suitable proportionality constant, it is possible to deduce E_a from the Arrhenius plot $\ln S_F$ vs $1/T$.[3]

The experimental points of Figs. 3 and 4 were obtained from different samples, and the data dispersion is not surprising; in fact, the noise power spectrum largely depends on the microscopic structure of the film and, hence, it changes, even under the same test conditions, from one sample to another. By comparison, Fig. 5 shows two Arrhenius plots obtained from a single resistor of the R1 and R2 series, respectively.

The first noticeable result that can be deduced from these plots is that the activation energies are 0.64 and 0.94 eV for R1 and R2, respectively; that is to say, E_a is greater for the Al-Si (1%) films than for the Al ones. Both values are in good agreement with the most probable values reported in the literature for Al and Al-Si (1%) film.[8,9] Besides the value of E_a obtained from Al-Si (1%) samples showed that, in the explored temperature range, the prevailing phenomenon was the diffusion of Si atoms along grain boundaries.[9] It must be observed, as will be seen subsequently, that these activation energies were obtained in conditions of very weak

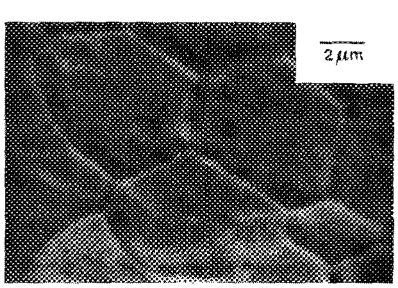

FIG. 2. Grain structure of an Al resistor.

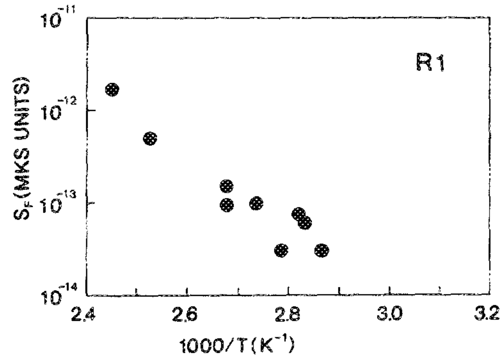

FIG. 3. Experimental points $S_F = S_R T/\rho j$ vs $1/T$ for Al resistors.

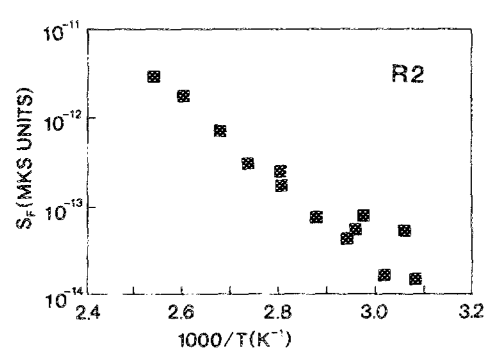

FIG. 4. Experimental points $S_F = S_R T/\rho j$ vs $1/T$ for Al-Si (1%) resistors.

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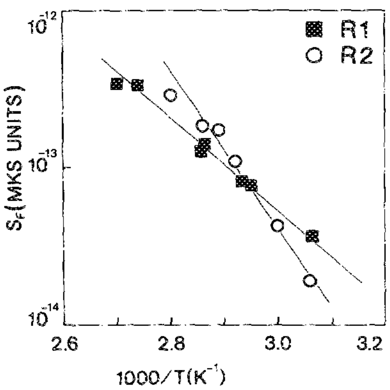

FIG. 5. Arrhenius plots from single resistors.

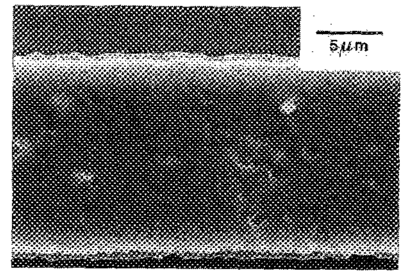

FIG. 7. Al resistor ($j = 1.8 \times 10^6$ A/cm^2, $T = 348$ K).

stress. The EM-induced damage, observed in the stressed resistors using a SEM, consisted of holes and cracks which were generally located at the triple points of the microcrystalline structure.

Figure 6 shows the plot of a damage variable D as a function of S_R (20 mHz) (and, hence, through the relationship 3, of the vacancy flux J_V) measured before the stress test, both for R1 and R2. The damage variable D is defined as the ratio between the surface density of the EM-induced defects and the density of the triple points.

As can be seen, the SEM observable damage after a 30-h stress, decreases with S_R (20 mHz), both for R1 and R2 series, and becomes undetectable at noise levels well above the background noise. The dependence of damage variable on S_R values strongly supports the hypothesis that the observed noise was caused by electromigration.

Before the SEM observation of the samples, their percentage resistance variation $\Delta R/R_0 = (R - R_0)/R_0$ was measured. R_0 and R are the values of the resistance before and after the stress test, respectively. It was found that the highest values for R1 and R2 series were 7×10^{-2} and 6×10^{-2}, respectively.

Finally, in order to demonstrate the sensitivity of the noise technique in detecting electromigration, an Al-Si (1%) resistor was subjected for a long time ($\simeq 1700$ h) to a current density for which the EM noise was slightly higher than the background one. After this time interval, the percentage resistance variation $\Delta R/R_0$ was 2.8×10^{-2}, whereas after 50 h the percentage variation (8.3×10^{-4}), deduced by assuming a linear behavior for the resistance change, was below the accuracy of the measurement system ($\pm 10^{-3}$) and hence, from a macroscopic point of view, this would lead to the conclusion that no electromigration at all has taken place. Figures 7 and 8 are examples of the damage induced by low- and high-stress conditions in Al samples.

In order to explain the meaning of high-stress condition, reference should be made to Fig. 9, where the $1/T$ range explored in the present work is compared with those explored using other techniques. It is evident that our higher temperature limit coincides approximately with the lower one made possible by methods based on the measurement of *macroscopic* variations of physical quantities.

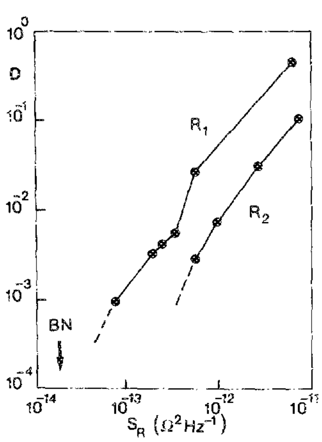

FIG. 6. Damage vs resistance power spectrum S_R.

CONCLUSIONS

In this work a systematic attempt was made to correlate EM spectra in a low-frequency range (10 mHz–1 Hz) and damage in Al and Al-Si (1%) resistors. It is shown that using an ultralow-noise amplifier, electromigration can be detected in a short time (4 h) and under stress conditions in which other methods (SEM observation and $\Delta R/R_0$ measurement) do not reveal any appreciable signs of damage.

Furthermore, the sensitivity of the new method makes it possible to evaluate activation energy in stress conditions which do not alter the microstructure of the sample during the measurement time. It should be underlined in this connection that a sample subjected to the minimum current density and temperature at which the EM noise exceeds the background one, should show a $\Delta R/R_0$ of about 8.3×10^{-4}, only after a 50-h stress.

The E_a values obtained both for Al and Al-Si (1%) resistors, i.e., 0.64 and 0.94 eV, respectively, are in agreement with those reported in literature. In the case of Al-Si (1%) resistors the E_a value would appear to indicate that, under the measurement conditions employed ($1.3 \times 10^6 \leqslant j \leqslant 2.25 \times 10^6$ A/cm^2 and $320 \leqslant T \leqslant 400$ K) the main phenomenon is the diffusion of Si atoms along the grain boundaries.[9]

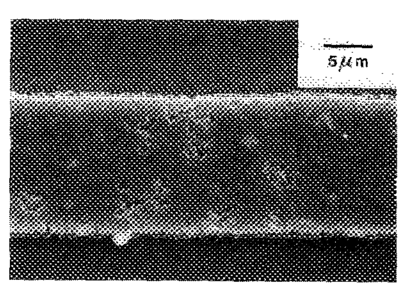

FIG. 8. Al resistor ($j = 2.2 \times 10^6$ A/cm^2, $T = 365$ K).

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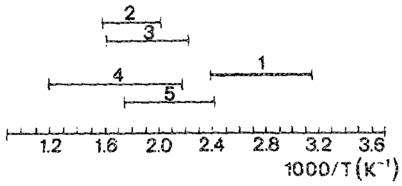

FIG. 9. Comparison among the $1/T$ range 1 (noise technique) and $1/T$ ranges 2 (resistance change [10]), 3 (void growth [11]), 4 (drift velocity [12]), and 5 (lifetest [13]).

main phenomenon is the diffusion of Si atoms along the grain boundaries.[9]

ACKNOWLEDGMENTS

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