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Activation energy for electromigration in Cu films

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Copper is a possible substitute for Al in very large scale integration interconnects because of its higher resistance to electromigration damage (EMD) and its lower electrical resistivity. In the present work, we report on electrical resistance measurements of the activation energy for EMD in Cu films as determined by an isothermal annealing method carried out under high vacuum conditions. Temperature measurement and control were accomplished by means of a Cu thin-film thermistor. The activation energy for EMD of evaporated Cu films was found to be 0.79 ± 0.02 eV.

Electromigration phenomena in thin films have been studied intensively since the mid 1960s when they were found to be the primary cause for the failure of Al interconnects in microelectronics.[1-3] Additives such as Cu, Ti, and Pd have increased the lifetimes of the interconnects. Current efforts, however, to decrease the width of the metal stripes to low submicron values for ultralarge scale integrated circuits demand materials with still greater resistance to electromigration damage (EMD). Recently, Cu has been considered as a possible substitute for Al.[4] While bulk Cu was known to have greater EMD resistance, lower resistivity, and a lower thermal expansion coefficient than bulk Al, it has not been used as an interconnect material because of the following reasons: (i) it is easily contaminated and corroded, (ii) it is difficult to etch, (iii) it has poor adhesion to oxidized silicon wafers. Recently, however, some success has been achieved in solving these problems. In particular, adhesion has been improved significantly by employing very thin interlayers. It has also been suggested that a protective coating of electroless Ni be used on Cu films which were deposited by a selective electroless method on an already patterned Ti layer.[4] Copper films have greater EMD resistance than Al films, which have an activation energy in the range of 0.43–0.55 eV.[5,6] Estimates of the median time to failure(MTF) for Cu films have used a value of 1 eV.[7] However, measurements of the exact value of the activation energy have not been reported yet. In this letter, we report the value of the activation energy for EMD in vacuum-evaporated Cu films as obtained by an isothermal electrical resistance method.

Measurements of electrical resistance changes with time for EMD were made by Rosenberg and Berenbaum[8] and by Hummel *et al.*[9] The time rate of change of electrical resistance due to EMD, dR/dt, is thermally activated and can be expressed by the following equation:

$$(dR/dt)x(1/R_0)=Aj^n \exp(-Q/kT), \qquad (1)$$

where R_0 is the initial stripe resistance, A is a pre-exponential factor, j^n is the electron current density raised to the power of n, and Q is the activation energy for EMD. Plotting the logarithm of dR/dt vs $1/T$ for constant j should result in a straight line, where the slope would give Q. The condition of constant current density j is important. The formation of large voids and hillocks during the catastrophic phase of EMD just prior to failure leads to increasing deviation from this condition. In the current study the change in resistance due to EMD at each isothermal annealing measurement was limited to about 0.5% and the total change in resistance after all the isothermal annealing measurements were completed was kept below 5%. Furthermore measurements of very small resistance changes that occur are affected significantly by correspondingly small errors in temperature measurement. It is therefore necessary to employ a highly accurate temperature measuring system. For this reason, we developed a thin- film thermistor technique and used it to carefully measure and control the temperature of the stripe in which EMD was occurring.

Pure copper (99.9999%) was evaporated to a thickness of 3000 Å onto oxidized silicon wafers from tungsten baskets in a high vacuum (HV) of 3×10^{-7} Torr. The specimens were annealed *in situ* at 450 °C for 30 min prior to air exposure. For good adhesion of the Cu film to the substrate and before the main Cu evaporation, various combinations of thin (20–50 Å) interlayers of Al, Cu, and Ti were evaporated and then oxidized in air at 330 °C for 30 min. These very thin interlayers provided sufficiently good adhesion for the subsequently deposited Cu films to pass an adhesive tape test. Low rate evaporation and low-temperature annealing were also effective for improving the adhesion of Cu films. In the patterning process, common photolithography was employed and a commercial Al etchant was used. The final specimen pattern is shown in Fig. 1. 3 mil Al wires were bonded onto the pads of the specimen with an ultrasonic wire bonder. In Fig. 1, pads *a*, *b*, *c*, and *d* were the current connections while *e*, *f*, *g*, and *h* were used to read voltages with a precision of 1 μV. One stripe in Fig. 1 was used as a thermistor for temperature measurement. The other one was used for the EMD measurements. Significant oxidation of the Cu films during the experiments was avoided by carrying out the entire EMD tests in the HV system.

A current of 1 mA(2.4×10^4 A/cm^2) was used to measure the temperature dependence of the stripe resistance. This current density was small enough to avoid causing significant EMD or Joule heating effects. The current was passed through both stripes as the substrate temperature was increased to 450 °C at a rate of 3 °C per minute.

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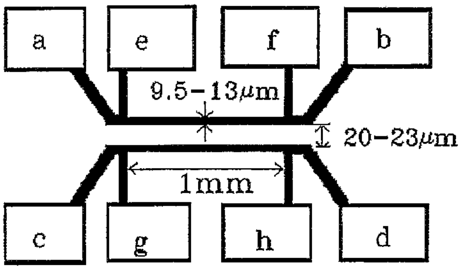

FIG. 1. Schematic diagram of the copper stripes. One stripe was used as the main stripe for EMD tests and the other was used as a thermistor. Dimensional ranges for the four stripes are indicated.

Chromel-alumel thermocouples (5 mil diam.) were placed 5 mm apart around the stripes for temperature measurement and control. During this experiment, the computer recorded data every 20 s. During the EMD experiments, however, Joule heating in the stripe undergoing EMD introduced a temperature gradient between it and the thermistor. This temperature gradient was measured as follows. A 1 mA current was passed through the thermistor. Simultaneously, but in two separate experiments, 130 mA (3.3×10^6 A/cm^2) and 340 mA(8.7×10^6 A/cm^2) were passed through the EMD stripe while its temperature was increased to 350 and 260 °C, respectively, at a rate of 3 °C/min. Measurements after this calibration process indicated that there was no significant change in resistance due to EMD. Figure 2 shows the relation of the main stripe resistance to the thermistor resistance with currents of (i) 1 mA through both stripes (line *a* in Fig. 2) , (ii) 1 mA through the thermistor and 130 mA through the main stripe (line *b* in Fig. 2), and (iii) 1 mA through the thermistor and 340 mA through the main stripe (line *c* in Fig. 2). The dotted line *d* is an extrapolation of the solid line *c*. Comparing lines *b* and *c* with *a* shows that (a) the temperature of the main stripe at high current density is not the same as that of the thermistor because of the Joule heating effect of the main stripe, (b) the Joule effect increases with current density and stripe temperature, and (c) the resistance of the main stripe increases linearly with that of the thermistor. This linear relationship was used to justify extrapolating line *c* to the high-temperature region. In this way the temperature of the main stripe can be obtained from the resistance of the thermistor during the EMD experiments.

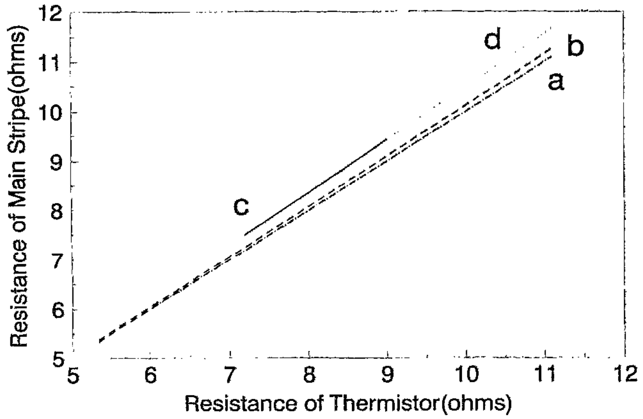

FIG. 2. Relation of resistance between the thermistor stressed at 2.4×10^4 A/cm^2 and the main stripe stressed at (*a*) 2.4×10^4 A/cm^2, (*b*) 3.3×10^6 A/cm^2, and (*c*) 8.7×10^6 A/cm^2. Line *d* is an extrapolation of line *c*.

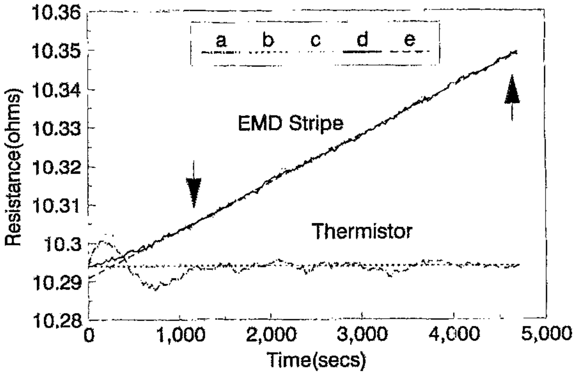

FIG. 3. Resistance fluctuations on an enlarged scale at 342.4 °C for thermistor (*a*: raw data, *b*: average of *a*) and EMD stripe (*c*: raw data, *d*: after correction on *c*, *e*: least- squares linear fit to *d*).

Measurement of the activation energy for EMD involved stressing the main stripe with a current density of 8.7×10^6 A/cm^2 at a series of temperatures. Each temperature was held constant, within experimental error, until the resistance increased by about 0.5% of the initial resistance. Then it was increased rapidly to the next temperature. The resistance changes due to EMD were measured at nominal temperatures of 282.2, 311.7, 342.4, 370.8, and 400.9 °C. Accurate calculation of the time rate of change of resistance required the application of a correction process to the raw data because there were slight fluctuations about the nominal temperatures. Figure 3 shows the resistance fluctuations on an enlarged scale at 342.4 °C for the thermistor (curve *a*) and the EMD stripe (curve *c*). The thermistor resistance values were increased by a constant 0.827 Ω in order to show them conveniently in the figure. The raw data show the extent by which the temperatures of the stripes were fluctuating, namely, by approximately ±0.2 °C. Neglecting these fluctuations was enough to give significant errors in the rate of change of resistance. A 0.4 °C deviation corresponds to an 0.08% deviation in stripe resistance. This deviation in resistance corresponds to more than 10% of the resistance change due to EMD. As mentioned previously, the experiments were designed to obtain EMD resistance changes of only several tenths of a percent (about 0.5%) at a given temperature. Thus, the effects caused by temperature fluctuation had to be eliminated from the raw resistance data. The following equation was used for data correction:

$$R_{c,m,T}=R_{r,m}-(R_{r,\mathrm{th}}-R_{\mathrm{th},T})(dR_m/dR_{\mathrm{th}}). \qquad (2)$$

$R_{c,m,T}$ is the corrected value of the main stripe resistance at a particular nominal temperature T, $R_{r,m}$ is the raw measured value of the main stripe resistance, $R_{r,\mathrm{th}}$ is the raw measured value of the thermistor resistance, $R_{\mathrm{th},T}$ is the

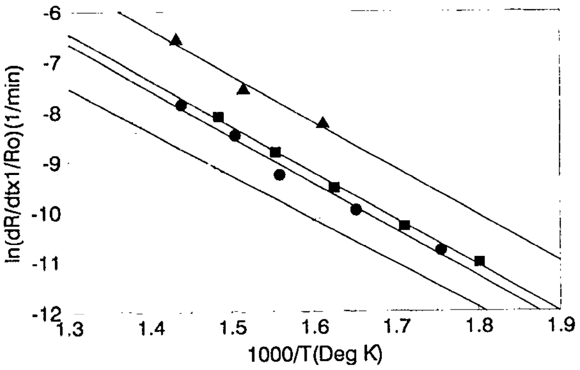

FIG. 4. Arrhenius plot of Eq. (1). Activation energies in eV for four different Cu films were 0.80 (▲: 9 MA/cm^2, 20 Å Al oxide interlayer), 0.80 (■: 8.7 MA/cm^2, 40 Å Cu-Al oxide interlayer), 0.80 (●: 9.4 MA/cm^2, 40 Å Cu-Al oxide interlayer), and 0.76 (○: 9.4 MA/cm^2, 50 Å Ti oxide interlayer).

exact value of the thermistor resistance at the main stripe temperature T, dR_m/dR_{th} is the slope of line *c* in Fig. 2. The corrected resistance changes of the main stripe are shown as curve *d* in Fig. 3. Line *e* was drawn as the least-squares analysis fit to the region of curve *d* located between the arrows. Line *b* was drawn to show the thermistor resistance at the main stripe temperature of 342.41 °C if there were no temperature fluctuations. Figure 4 shows the Arrhenius plot derived from Eq. (1) for four different films having slightly different current densities in the range of 8.7–9.4 MA/cm^2. The slopes of the lines give the activation energies. The average value is 0.79 ± 0.02 eV. In the case of bulk, polycrystalline Cu wires of 1 mm diameter, the activation energy for EMD was reported to be 2.1 eV by Sullivan.[10] No microstructural characterization was given in this report. These wires were tested above 1000 °C and thus surely had large grain sizes, most likely also with grain boundaries perpendicular to the wire axis. In such cases, grain boundary diffusion parallel to the wire axis would be difficult and thus lead to a high activation energy for EMD.

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