Electromigration in Single-Crystal Copper Whiskers

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Applying current through a single-crystal copper wire causes periodic structures to develop in a region of the surface where temperature is highest. These structures move along the wire until the wire breaks. This motion of atoms along the surface of the metal when current is flowing is surface electromigration. The electromigration in single-crystal copper has been measured for the first time and is shown to have a velocity of 0.20 microns/sec. A method was developed to use dR/dI data to infer the temperature on the wire during electromigration. Finally, a method was initiated to validate the temperatures predicted by the thermal model.

I. INTRODUCTION

The behavior of current flow through microscopic wires is of special interest to designers of integrated circuits. As the size of chips become smaller, the current density flowing through the microscopic wires on the chip increases, introducing electromigration in the wires. Electromigration is the migration of atoms across a metal in the presence of an electric field, that is, when current runs through the metal.

Electromigration has two primary causes. First, lattice atoms are driven by momentum transferred from the moving electrons and second, the lattice atoms interact with the electric field present in the metal and feel an electrostatic force [1]. In copper, momentum transfer is the dominant mechanism. If sufficient current is run through a metal wire, the migration of atoms will cause the wire to break. It is this failure of microscopic wires due to electromigration that is of interest in integrated circuit fabrication.

Copper is a metal of choice in designing solid state circuits due to its high conductivity. The focus of this investigation to observe and understand electromigration in single-crystal copper whiskers. Whiskers describe wires typically between 5 and 10 microns in diameter.

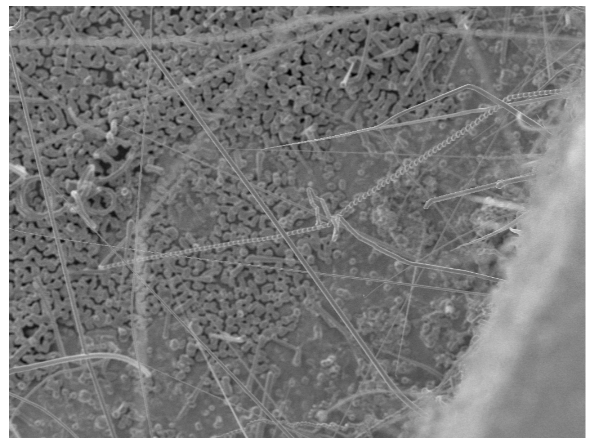

FIG. 1: Whiskers in the Copper Boat. This is an SEM image of an area of the copper boat after whiskers have grown. Wires that appear smooth and uniform are selected from this boat to be studied.

II. THEORY

Observations from a previous electromigration experiment had been used to create a model to predict the behavior of the wire when current is applied. The model predicts that a cylindrical wire can develop carrot-like features which move along the wire. The model is described by a partial differential equation [5]. A separate model of the thermal properties of the wire is used to predict the temperature along the wire. The parameters are diameter at each end of the wire, its length, and the current estimate as well as the materials properties of copper. The function uses these parameters to generate a table of current, temperature, resistance, and dR/dI. This table serves as a guide during the experiment to predict when the wire will break due to melting. The model makes the assumption that the temperature at either end of the wire is 293 K. A plot of temperature as a function of distance along the wire shows a parabola, predicting the maximum to be where the temperature is highest. This area of interest is the focus of imaging during the experiment because where the temperature is highest, the most geometry changes are expected and the wire is expected to break.

The model makes a prediction of what the temperature along the wire is, but there is no direct way to measure the actual temperature along the wire. An indirect method for measuring the temperature would provide an additional parameter to further refine the model. The following is the one scheme for measuring temperature that was developed. Silver and copper form a eutectic with a melting point lower than both silver and copper. A region of silver is evaporated on the copper wire to encompass the area of interest. When applying current to the wire, it is expected to break (melt) at a current value lower than copper itself due to formation of an Ag-Cu eutectic. Using the weight percent of each metal, the temperature where this break occurs is known. The comparison of this temperature-current value to the models prediction for temperature at the given current value validates the accuracy of the model.

III. EXPERIMENT

A. Sample Preparation

Copper whiskers are grown from a copper halide solid. The wires used in this experiment were grown from 200 grams of copper (I) bromide. The Cu(I)Br is placed in a copper boat and inserted into the center of a tube furnace. Hydrogen gas is flowed through the chamber. After 15 minutes 590 degrees C the hydrogen gas and furnace are shut off and the sample is allowed to cool in the closed chamber until reaching room temperature. The boat now contains a larger number of the single-crystal copper whiskers. Fig. 1 shows whiskers in the sample boat.

Under an optical microscope, a whisker that appears smooth and without imperfections is selected from the boat and placed across a chasm on the sample mount. The sample mount is designed to hold four wires with individual electrical connections and a common ground. Fig. 2 shows the sample mount. The distance between the mounts is adjustable and is set between 1 and 2 mm. The wire is held to the mount with a dot of colloidal silver paint at each end, and baked in an oven under a light vacuum for about 2.5 hours at 110 degrees C to dry the paint.

The sample is loaded into the Scanning Electron Microscope (SEM), which has been adapted to make electrical connections to outside the sample chamber. Each wire on the sample mount is connected to one of twelve ports inside the chamber that leads to a BNC connector outside. A very slow diffusion of forming gas (5 percent hydrogen, 95 percent nitrogen) is introduced to the chamber to produce a reducing atmosphere that will prevent the copper from oxidizing. The chamber is pumped down to vacuum, about 10 -5 torr.

Images of the sample inside the chamber are taken using the computer software AnalySis. Each wire is inspected for unusual features along the surface and the entire length and each end of the wire are imaged. Measurement tools in the AnalySis software are used to determine the diameter at each end and the total length of the wire from the images. These three measurements and a maximum current estimate serve as the input parameters to the model to predict the temperature along the wire.

B. Part I: Basic Experiment

A Keithley 2400 SourceMeter supplies constant current across the wire, and is controlled by a LabView program,

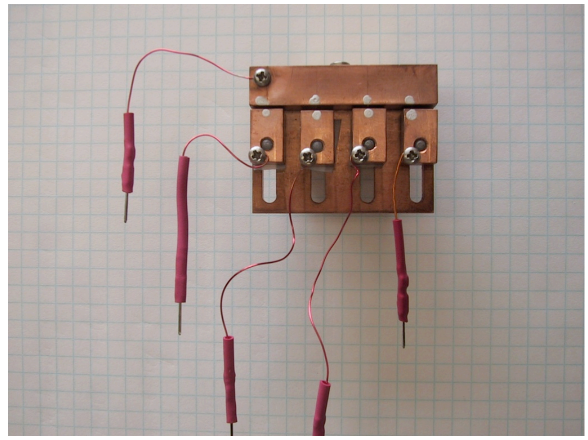

FIG. 2: The Sample Holder. A copper whisker extends across each chasm, fastened by a dot of silver paint on either side. The wires are attached to the current supply and ground through connections in the wall of the SEM chamber.

which allows the user to enter a current value to run across the wire and measures and records the voltage, current, and resistance of the wire. The program also uses this data to produce a real-time plot of the resistance and the change in resistance with current (dR/dI) as a function of time.

The SEM is focused on the area of interest and this is where imaging occurs. Using the models predictions as a guide, current is gradually increased. The wire is imaged at frequent intervals and when any kind of changes occur on the surface of the wire, the program is set to take pictures of the wire at regular intervals. At some maximum current value, the wire breaks. After the wire breaks, images are taken of other interesting features that developed. The images taken at the area of interest (AOI) are put together as successive frames in a video.

C. Part II: dR/dI Measurements

The LabView program generates tables of voltage, current, and resistance throughout the experiment. However, the resistance is due not only to the wire, but also to the leads, contact resistance, etc. Thus it is impossible to directly relate the resistance readings to the wire properties.

Plotting dR divided by dI (dR/dI) as a function of current is a way to compare the experimental data to the model quantitatively. The model predicts that a plot of dR/dI versus current should have the shape of an exponential plot. The maximum on the plot corresponds to the current value where the wire is expected to break, due to melting, thus this value is deemed the maximum current value.

The LabView program has a feature to measure dR/dI. Selecting this option at any time during normal function of the program asks for maximum current value, step size, and maximum dR/dI as input parameters. The program starts the current across the wire at an initial set current, then steps it up until a maximum current or a maximum dR/dI is reached. The output parameters are monitored on a display and used to generate a real-time plot of dR/dI versus current. Once a maximum is reached, the program resets to the initial set current. Multiple trials are made by varying the initial set current and changing input parameters so that the change in wire properties- primarily temperature- can be followed during the course of the experiment.

D. Part III: Silver Evaporation

Finally, a procedure was developed to evaporate silver onto the copper wire. The goal is to place enough silver on the wire to form a silver-copper eutectic. The Ag-Cu phase diagram indicates that the eutectic forms between 9 and 90 percent copper by weight, with the lowest temperature occurring around 28 percent copper by weight [4]. Using the equation to calculate evaporation thickness, a volume of silver is calculated to coat the exposed region of the wire with a 4 micron-thick layer of silver on a region of the wire 10 microns in diameter [3]. This is approximately 60 percent copper by weight.

A mask was created out of metal to screw onto the sample holder. This mask covers everything except the chasm where the wires are held. Under an optical microscope, two strips of metal are affixed with scotch tape to narrow the exposed area of the chasm. The sample except the mask is covered with foil and placed in the evaporator. Silver boats of varying size and a tantalum boat were used.

After depositing the silver, the usual procedure is followed to acquire data on the wires. First, the predictions of the model are used as a guide to obtain dR/dI data. Second, the dR/dI data is analyzed with the rectangular hyperbolic fit function to make another prediction for maximum current. Third, an area of interest is chosen on the wire and images are taken as current is increased.

IV. RESULTS

A. Part I: Basic Experiment

The fundamental electromigration model predicts that a smooth wire will develop moving carrot-shaped lobes. These features have never been observed including in this study, except for that first time. The lack of carrot features is important because this makes direct comparison of the complicated observations with the simple model results impossible. The general trend in observations is that some kind of periodic geometry developed along the surface. Fig. 3 shows an example of a broken wire that developed periodic geometry. Most features tended to develop at the AOI, where the temperature is highest, and decreasing out towards either end, where the temperature is close to room temperature. Often the features then appeared to move along the wire. In several cases, individual features were identified and followed as they moved along the surface.

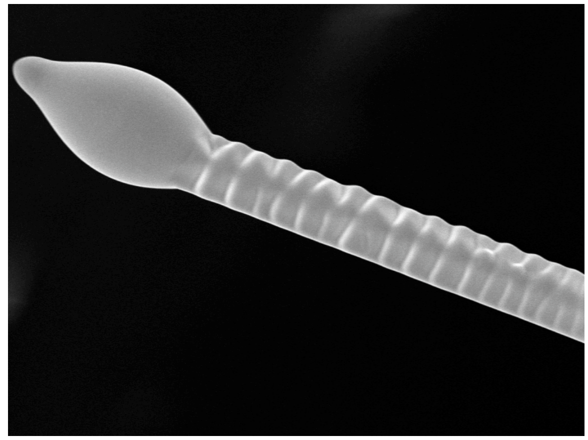

FIG. 3: A Broken Wire. The bulb side of the broken wire is shown. Periodic structure that developed while current was running is evident.

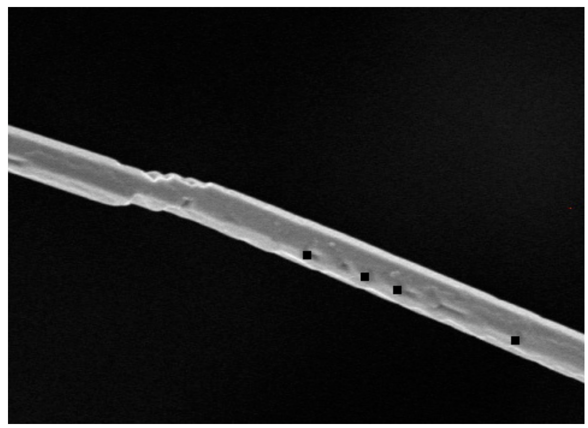

FIG. 4: Features on the Wire. The features marked on the wire with black dots were observed to move across the wire. The position and time data for each of these points in successive images were used to calculate an average velocity for features moving along the wire over a given range of current

The observation of features moving along the surface of the wire lends itself to a calculation of the features velocity. On the images acquired during one experiment, several features were selected and the x- and y-coordinates were measured, yielding the distance that a feature moves over time. One of these images is shown in Fig. 4. Fig. **??** shows a plot of distance versus time for several different features. The average of these velocities is 0.20 microns per second over an estimated temperature range of 500 to 650 degrees C. The temperature range is the thermal models prediction for the temperature corresponding to the current range of 93.5 to 95.5 mA over which the velocity was calculated.

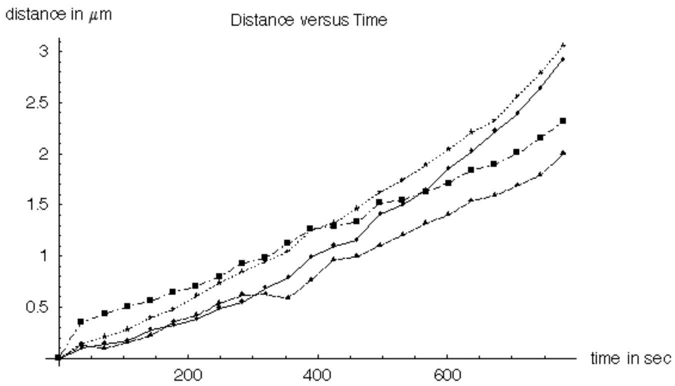

FIG. 5: Distance versus Time Plot. This plot shows four different results for features moving across the surface of the wire. The slope gives a value for the velocity of that feature.

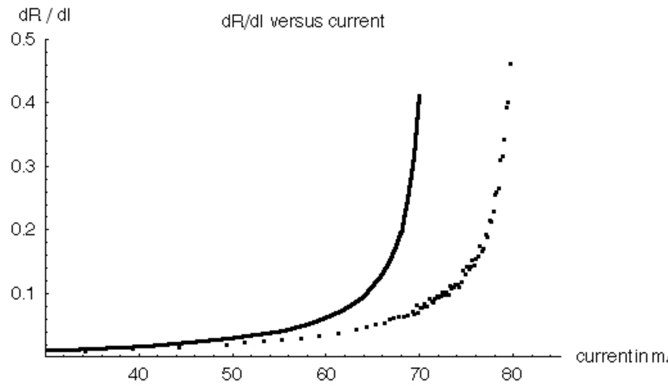

FIG. 6: dR/dI versus Current Plot. The bold line is the dR/dI versus I curve predicted by the model for a particular wire. The data points are the experimental results obtained from running current through this same wire.

This velocity value was compared to literature values for velocity in polycrystalline copper samples. Lee, Hu, and Tu looked at polycrystalline copper in tantalum enclosures [2]. Extrapolating their experimental conditions to match those cited above gives a velocity value of 0.034 microns/sec. This value is about 6 times smaller than our result for single-crystal copper. However, a smaller velocity in polycrystalline copper is expected because a polycrystalline sample has grain boundaries that would hamper the flow of atoms.

B. Part II: dR/dI Measurements

Comparing the dR/dI versus I plots generated for the data and model shows that the plots have the same characteristic exponential-like shape, but the vertical asymptote (the melting point) is shifted by a small amount. Fig. 6 shows an example of these plots. The vertical asymptote is a very sensitive function of the wire dimensions. A few percentage change in wire size (below the accuracy of the SEM measurements) is sufficient to bring the model and experiment into agreement.

There are four values for maximum current to compare. First, the value predicted by the thermal model. This value is sought to the nearest milliamp. Second, the value predicted by fitting a rectangular hyperbolic function to the model. Third, the average value of a fit to multiple runs of data over the same parameters. Fourth, the current recorded when the wire actually breaks. Table . I shows these values for seven different wires. These values will be compared in the discussion section.

C. Part III: Silver Evaporation

Evaporating silver onto the wire is proving to be a difficult process, but progress was made. Silver has been deposited on the wire. Under an optical microscope, silver is evident on the wire because of a change in the color. In the SEM, there is no clear indication of where the region of silver would begin and end. The change in thickness of the wire is not obvious because the diameter of the wire is not constant, and choosing the exact same region of the wire to measure before and after deposition is not possible in general. These comparisons usually showed a change of less than 1 micron in thickness. However, on some wires, the silver peeled away from the surface, showing a thickness between 1 and 2 microns.

During several experiments with silver on the wires, there were few general observations. In most cases, nothing happened on the surface until the wire suddenly broke. Most wires appeared to break violently, leaving a large glob on one side of the broken wire. In one trial, the silver in one area disappeared over a period of time at a set current value. The apparent disappearance of the silver is likely diffusion of the silver into the copper or movement of the silver to another place on the wire. This part of the project is still underway, and final conclusions have yet to be made.

V. DISCUSSION

It is important to point out that without the observation of the carrot-like features on which the model is based, direct comparisons to the simple electromigration model is not possible. However, the data shown in table I indicates that the thermal model, through the dR/dI measurements, is good for making predictions of the temperature profile of the wire. This is evident from the similar shape of the dR/dI versus current plots shown in the figure and in the table comparing maximum current values. For example, in wires 1.1 and 1.3, the current flowing when the wires broke were 6 percent and 5 percent larger than the model predicted, respectively. Other data not shown has similar low percentages in deviation

Predictions for Maximum Current (mA)					
Wire Number	Model	Fit to Model	Fit to dR/dI w/o Ag	Fit to dR/dI w/ Ag	Actual Breakage
1.1	262	268.32	-	-	278.4
1.3	242	244.17	-	-	254.0
4.1	191	193.33	128.58	-	-
4.2	166	167.92	157.36	-	-
4.3	249	250.54	-	-	334
5.1	69	71.04	79.00	79.47	80.2*
5.2	119	121.44	138.33	147.55	141.1*
5.3	196	198.18	198.77	206.41	203.5*
5.4	445	450.97	396.27	273.85	271.4*
* The wire was coated in silver when it was broken.					

TABLE I: A table or predictions for the maximum current value where the wire will break.

from the models prediction. The general trend is that the wire breaks at a higher current that predicted, but there are still anomalous instances when the wire breaks much higher than expected. For example, wire 4.3 broke at a current 34 percent larger than predicted.

The silver-copper eutectic method to validate the temperature model shows promise. While the results acquired did not provide a wealth of information, the observation of disappearing silver indicates that something is happening on the surface. More observations of this same result will lead to an understanding of what exactly is happening to the silver. Hopefully, this disappearance is an effect that occurs at a temperature predicted by the phase diagrams.

VI. CONCLUSION

The thermal model used at present to measure temperature in single-crystal copper whiskers is in good agreement with quantitative data. The silver-copper eutectic being used presently to validate the temperature is promising and requires more data to produce definitive results. The simple electromigration model is difficult to compare with the complicated observations. The complicated morphologies observed to develop on the surface agrees less with the models prediction, though there are trends of periodicity and motion in the observations. The observations do show electromigration and the velocity of a number of features due to electromigration was measured. Future work should be focused on refining the model by determining more parameters and increasing accuracy of known parameters. In all, important steps have been made in understanding electromigration in these single-crystal copper whiskers.

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