Rate Monitor for Chemical Etching of Copper Films

By H.H. Law, A. Borges, G. Robinson and M.D. Evans

Etching copper layers to yield reproducible fine line patterns is an essential operation in conventional hybrid circuit or printed circuit board fabrication. The etch rate is commonly monitored by the amount of copper etched from a copper layer with a known thickness, and it requires many thickness measurements to obtain the desired accuracy. A novel simple-to-use visual rate monitor has been developed for the copper etching operation, and it can be fabricated from inexpensive commercially available equipment in a straightforward manner. The etch rate measurement time is reduced to the residence time of the monitor in the etcher.

Etching metal layers chemically to yield reproducible fine line patterns is an essential operation in conventional hybrid circuit or printed circuit board fabrication. To obtain consistent etching performance, the etchant solution must be maintained and replenished, and the etch rate must be monitored and controlled. While the process control procedure depends on the etching chemistry, the etch rate is commonly monitored by the amount of metal etched from a metallic layer with known thickness for a given etching time. This practice of monitoring etch rate requires many thickness measurements in order to obtain the desired accuracy. The procedure can become time-consuming when numerous experimental investigations must be made to determine the optimal operating conditions or to evaluate equipment design issues, as in the case of incorporating a new etchant into an existing production process.

The ideal etch rate monitor (ERM) should be easy to use and self-contained. The measurement time must be short, so that the performance of the etcher will not change during the measurement interval. A monitor capable of continuously displaying the etch rate is very desirable, but a low-maintenance sensor for such a monitor must be developed.

For certain etchants, the etch rate depends greatly on the processing conditions. For instance, the etch rate of ammoniacal cupric chloride etchants is limited by mass-transport under all conditions and the etchant temperature affects the rate significantly.[1] An etch rate monitor for this class of etchant, accordingly, must be exposed to the same etching process as the parts in the etcher. The optimal rate monitor should be similar to the substrates etched. If a quartz crystal microbalance probe is used to measure the etch rate of copper films on flat circuit boards, the measurement would be different from the actual rate because of the probe's geometry.

To monitor the etching of copper films on flat board substrates, one simpler approach is to use a substrate with a graduated metal thickness. After the monitor substrate is processed through the etcher, the amount of metal etched will be directly indicated by the edge location of the metal layer. The portion of the monitor with a thickness less than the amount etched would be bare. With a thickness scale, an operator can determine the etch rate directly.

In this paper, the design and fabrication of a novel simple-to-use visual etch rate monitor[2] for the ammoniacal copper chloride etchant are described. The concept should apply to any system of chemically etching metal films where the underlying substrate visually contrasts with the metal layer. Results of the evaluation of the spray nozzle design and the minimization of the undercut and underetch of conductor lines are presented to illustrate the versatility of the etch rate monitor.

Monitor Description and Fabrication

The monitor is made by sputter-depositing a sequence of thin, conducting layers on a standard ceramic substrate (3.75 x 4.5 in.). The uppermost layer is copper, with an underlying thin adhesion layer of titanium or chromium. The varying copper thickness profile is created by electroplating with a nonparallel arrangement of the cathode and the anode. Figure 1 shows the schematic of the set-up, commonly known as a Hull cell. This arrangement has been extensively used for evaluating the performance of electroplating solutions in the

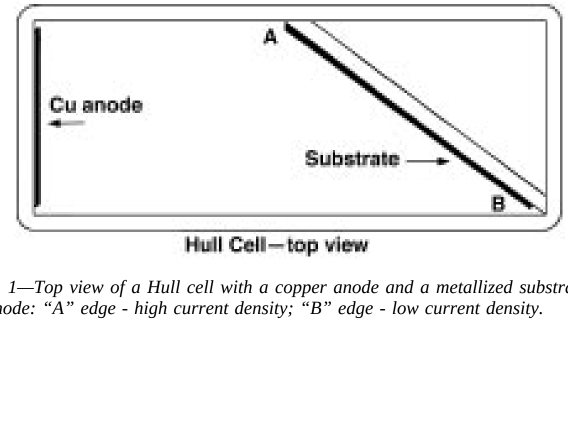

Fig. 1—Top view of a Hull cell with a copper anode and a metallized substrate as cathode: "A" edge - high current density; "B" edge - low current density.

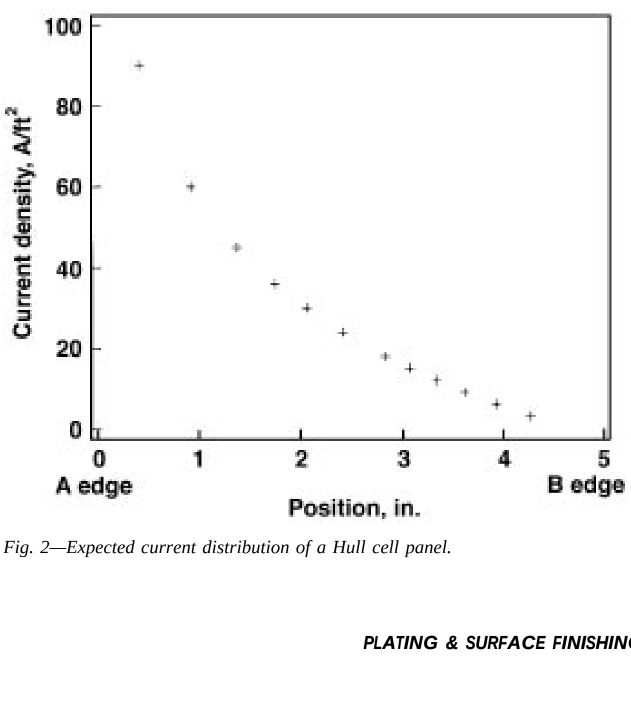

Fig. 2—Expected current distribution of a Hull cell panel.

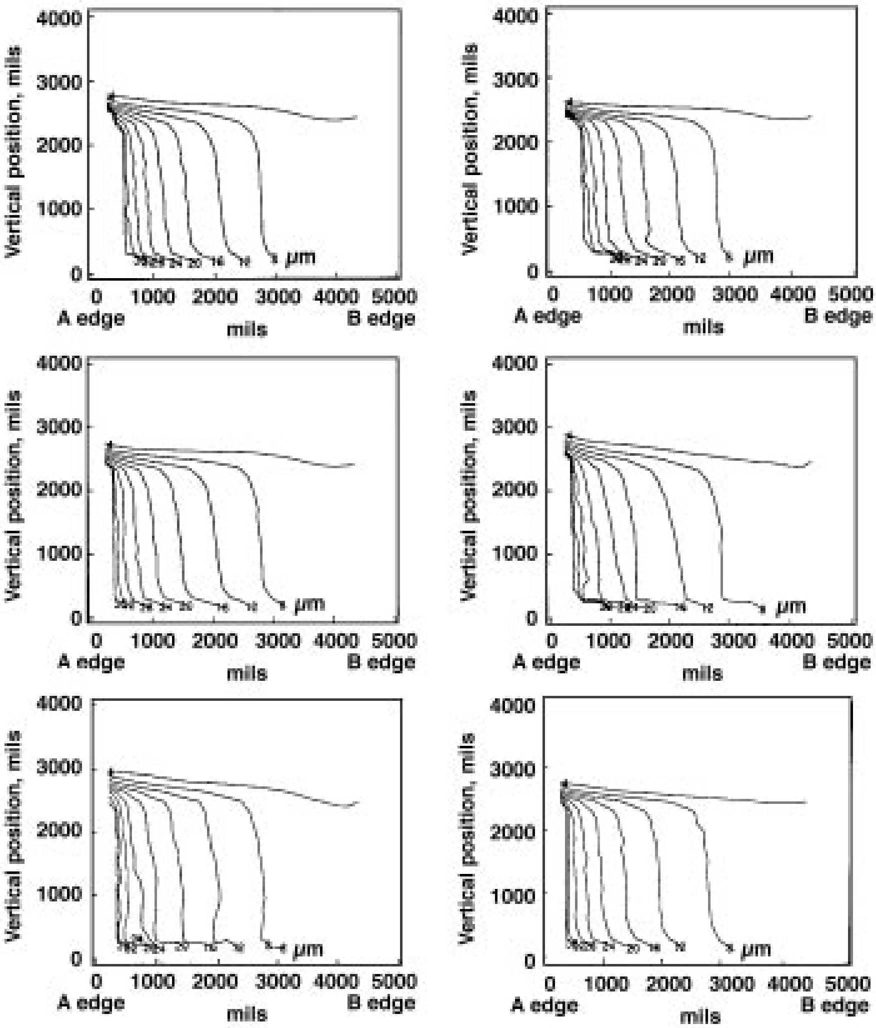

Fig. 3—Copper thickness contours (µm) of six randomly selected monitors.

plating industry.[3,4] The expected current distribution of a five-in. cathode panel with a current of 3 A is shown in Fig. 2 for a one-liter Hull cell. Because the substrate is 4.5 in. long, the monitors were fabricated using a standard one-liter Hull cell without any modification. For the current applications, a median thickness of 10 µm (400 µin.) was selected. The total plating current was 3 A and the plating time was 15 min.

To determine the reproducibility of the thickness profiles, 135 monitors were made and six were randomly selected for more systematic thickness measurements, using an X-ray fluorescence analyzer. A grid pattern with 4 x 4 mm spacing covering the center portion of an area 109 x 86.6 mm was made for each of the six monitors. The thickness measurements are plotted as contour maps (Fig. 3). A linear variation of thickness was found at the center of the substrate. To compare these monitors, thickness measurements at 1.5 in. from the bottom were grouped together and the average thickness values, as well as the maximum and minimum values, are depicted in Fig. 4. The variation at the center is the lowest. The table shows the standard deviation as a function of location.

With the known thickness profile, we can construct a linear scale to facilitate the reading of the amount of copper etched. Figure 5 shows the linear scale constructed from the data shown in Fig. 4. We have found that such a scale on a transparency is convenient.

Applications

Spray Nozzle Design Evaluation

The etch rate monitors have been used to evaluate the performance of spray nozzles with different designs. Figure 6 shows the amount of copper etched as a function of pressure for the same duration in the spray chamber for three different nozzle designs: Fan, Cone 10 SQ and Cone 14 SQ. In addition to demonstrating the effectiveness of the cone-type nozzle, the rate monitors also reveal the influence of other factors. Figure 7 shows the actual monitors with the remaining copper layer after being etched at a pressure of 25 psi with three different spray nozzle designs. The variations were caused by additional etchant dripping from the clamps holding the substrates. The

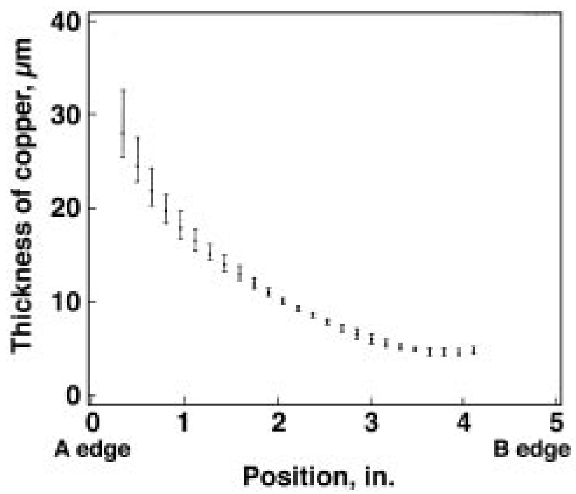

Fig. 4—Copper thickness profiles of six monitors at 1.5 in. from bottom; the maximum, average and minimum values are shown.

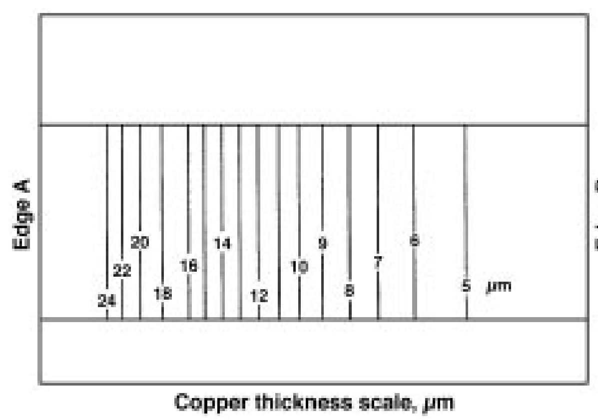

Fig. 5—Linear scale of the copper thickness of etch rate monitor.

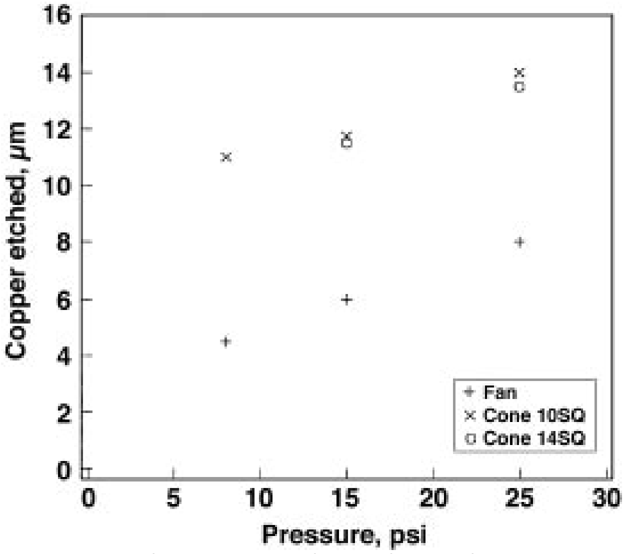

Fig. 6—Amount of copper etched as a function of pressure for three nozzle designs.

cone nozzle samples appear to have smaller variation than the fan nozzle. Similar profiles were observed under other experimental conditions. Accordingly, the cone nozzle offers faster etch rate and minimizes the effect of dripping from the substrate clamps. Obtaining similar information by etching a uniformly thick copper layer would require numerous thickness measurements on etched samples (*e.g.* a thickness mapping with 1 x 1 mm resolution for the whole substrate would require more than 10,000 measurements).

Minimizing Conductor Line Undercut and Underetch

The primary function of the etching operation is to form a pattern of conductor lines with specified physical dimensions from a metal layer. From the processing perspective, the etcher should be operated to minimize the undercut and underetch of the conductor lines of targeted thickness, that is, to form vertical wall conductor lines with desired thickness and width. In spray etching processes, the extent of undercut and underetch are affected by many factors. For a given etchant chemistry, the current rate monitor would indicate the amount of copper etched per pass, which combines the effects of many processing variables, including etchant temperature, the spray nozzle design and its operating pressure, the part residence time, etc. In this section, the usefulness of the etch rate monitor in carrying the minimization studies of undercut and underetch is illustrated. As illustrated in Fig. 8, undercut is defined as half of the difference between the base line width (BLW) of the etch mask and the top line width (TLW) of copper, and underetch is half the difference between the etch mask base line width and the copper base line width of the conductor line. In spray etching processes, the extent of undercut and underetch are affected by many factors. For a given etch chemistry, the current etch rate monitor indicates the amount of copper etched per pass, which combines the effects of many processing variables, including etchant temperature, the spray nozzle design and its operating pressure, the part residence time, etc. In this section, the usefulness of the ERM in carrying the minimization studies of undercut and underetch is illustrated.

An etch rate monitor substrate was patterned with 40

Variation of Thickness Values

Location in.	Average thickness, μm	Standard deviation, μm	Max. μm	Min. μm
4.11	4.66	0.23	5.00	4.37
3.95	4.55	0.19	4.89	4.37
3.79	4.65	0.18	4.94	4.48
3.64	4.77	0.19	5.12	4.58
3.48	5.02	0.16	5.28	4.79
3.32	5.36	0.23	5.59	4.99
3.16	5.76	0.38	6.34	5.22
3.00	6.16	0.39	6.81	5.71
2.85	6.70	0.36	7.33	6.36
2.69	7.35	0.29	7.88	7.10
2.53	8.04	0.25	8.50	7.83
2.37	8.74	0.21	9.04	8.54
2.22	9.51	0.32	9.95	9.22
2.06	10.43	0.35	10.92	10.03
1.90	11.37	0.42	11.96	10.87
1.74	12.30	0.47	12.99	11.69
1.58	13.40	0.52	14.12	12.75
1.43	14.46	0.55	15.39	13.78
1.27	15.55	0.68	16.44	14.73
1.11	16.98	0.82	18.36	16.07
0.95	18.47	0.89	19.58	17.23
0.79	20.32	1.30	22.20	18.64
0.64	22.50	1.31	24.28	21.00
0.48	25.11	2.83	28.79	21.55
0.32	28.67	2.66	32.24	25.83

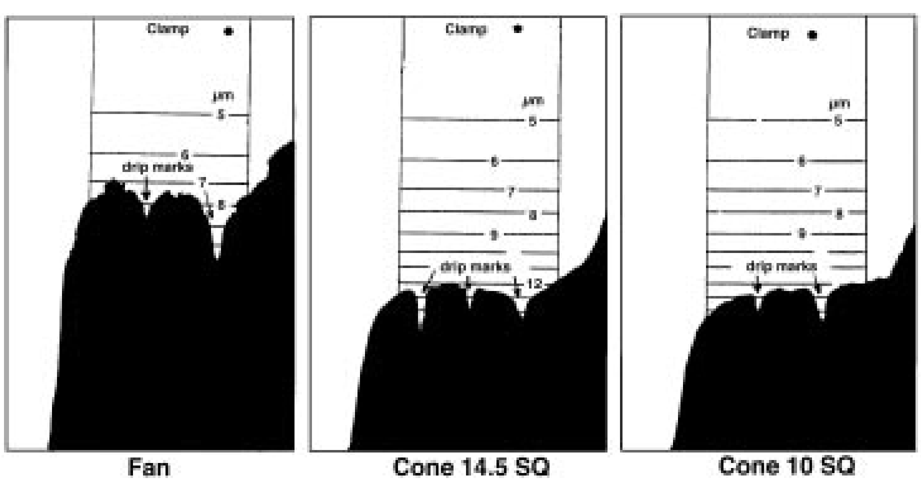

Fig. 7—Three of the etch rate monitors reported in Fig. 6.

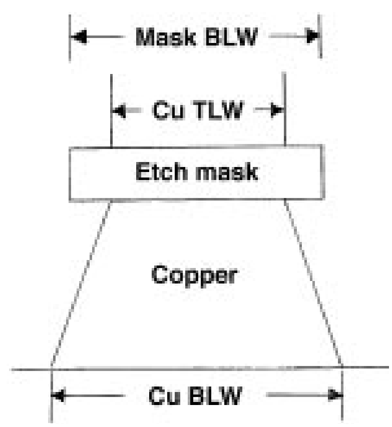

Fig. 8—Schematic of an etched conductor profile.

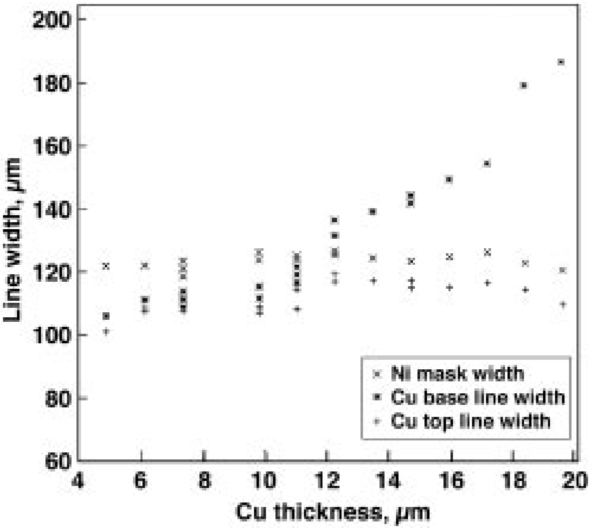

Fig. 9—Plot of mask base line width, copper top line width and copper base line width, vs. copper thickness.

parallel 5-mil-wide lines covering a 10-cm-long region along the direction of varying copper thicknesses. With plated gold over nickel as the etch mask, the metallization was etched in a production conveyor etcher. The copper thickness, the nickel mask base line width and the copper top line width were measured from the cross-section of each conductor line. The copper-base line width was measured only for conductor lines with a thickness less than 20 μm because the copper layer was not etched through at higher thicknesses. Consequently, the etch rate was 20 μm per pass. The measurement accuracy and resolution were about 1.2 μm.

The undercut and underetch of the conductor lines were found to depend on the copper conductor thickness. In Fig. 9, the plot of the nickel mask base line width (adjacent to the copper), the copper top line width and the copper-base line width vs. the copper thickness indicates strikingly that both the undercut and the underetch are minimal at a copper thickness of about 12 μm. The presence of the etch mask appears to slow the mass transfer near the conductor wall and reduce the etch rate. In terms of forming vertical-wall conductor lines, the etcher was operated to form 12-μm-thick copper lines and only one run was needed to determine the optimal thickness.

The usefulness of the etch rate monitor in minimizing the underetch and undercut has been shown. The actual etch rate of copper away from the etch mask was 20 μm per pass while the actual etch rate on forming vertical-wall conductor lines was only 12 μm per pass. If the spray etcher were set, using blanket copper substrates as rate monitor, to form 20-μm-thick and 120-μm-wide copper conductor lines, then significant underetch would have occurred. The conductor base line width would have been 180 μm, much wider than the expected width (etch mask base line width) of 120 μm. With the present etch rate monitor, it is much easier to optimize the spray etcher operation to accommodate any metallization processing changes.

Summary

A novel, simple-to-use visual rate monitor has been developed for the copper etching operation. It is made of a substrate with a copper layer having a graduated thickness profile. The monitor fabrication is straightforward and uses inexpensive, commercially available equipment. Because the thickness profile is well-controlled, the need for evaluation of the copper thickness is limited to the few measurements required for quality control of the monitor fabrication. The etch rate measurement time is reduced to the residence time of the monitor in the etcher. Etching rate monitors were found to be useful in the evaluation of spray nozzle design and in the optimization of etcher operating conditions to form vertical-wall conductor lines with specific thickness and line width.

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