J Appl Electrochem (2008) 38:1495–1500
DOI 10.1007/s10800-008-9594-3

ORIGINAL PAPER

Improved shape evolution of copper interconnects prepared by jet-stream etching

**Tsung-Kuang Yeh · Ming-Han Tsai ·
Mei-Ya Wang · Chen-Kuo Weng**

Received: 11 December 2007 / Accepted: 12 May 2008

Abstract In the preparation of copper interconnects in the conductor pattern of a printed circuit board (PCB), wet etching processes are commonly adopted for creating patterns of high-density interconnects. Currently available techniques of immersion and spray etching could lead to poorly shaped wires due to complex flow fields or the disturbing puddling effect. A modified technique of arrayed jet-stream etching was developed in this work, aiming at producing well-defined copper interconnects on a PCB in a significantly shorter time. The results were appealing in that copper interconnects of 35/140 μm (thickness/width) exhibiting etching factors of greater than 6 were obtained in 20 s, much better than the conventional ones with etching factors of 3 to 5 and etching times of at least 2 min. In addition, uniformly etched copper interconnects with less than 20 μm undercuts were observed on one etching line. One additional point to note is that no banking agents or inhibitors as commonly seen in conventional etching techniques were needed in this new processing method.

Keywords Copper interconnect · Printed circuit board · Jet stream · Etching factor · Anisotropy

T.-K. Yeh (✉) · M.-Y. Wang
Nuclear Science and Technology Development Center, National Tsing Hua University, 101, Sec.2, Kuang Fu Rd, Hsinchu 300, Taiwan
e-mail: tkyeh@mx.nthu.edu.tw

T.-K. Yeh · M.-H. Tsai
Department Engineering and System Science, National Tsing Hua University, Hsinchu, Taiwan

C.-K. Weng
Weltone Enterprise Co., Ltd, Taoyuan, Taiwan

1 Introduction

Copper interconnects are commonly used in the core components of a wide variety of modern electronic products. They are generally present in integrated circuit (IC) chips in size of tens of nm, in printed circuit boards (PCBs) in size of tens to hundreds of μm, or in lead frames in size of a few hundred μm. For preparing fine, nano-sized interconnects in IC chips, an additive method of electrochemical deposition is generally used [1–3]. For those in PCBs and lead frames, however, a subtracting method of wet chemical etching is the conventional approach [4–14]. The additive method of electrochemical deposition is not suitable for fabricating interconnects on PCBs since it is relatively time-consuming and more expensive. Copper interconnects on PCBs appear in all sorts of digitized electronic devices such as personal computers, personal digital assistants, digital audio and video players, mobile phones etc. To meet the increasing demand on small portable devices, the size of a PCB has been significantly reduced and so has that of the copper interconnects on both sides of the PCB.

In the preparation of copper interconnects on a PCB by wet chemical etching, the surface of the PCB substrate (usually a reinforced fiberglass plate filled with epoxy) is usually laminated with a copper foil of tens of μm, followed by a thin layer of photoresist (PR). Prior to the etching process, the PR is deliberately patterned by photolithography to serve as a mask for the underlying copper foil. The quality of the etched copper interconnects may be quantified, as shown in Fig. 1, by an etching factor (E_{ind}) that is commonly defined by the modern PCB industry as the ratio of the etching depth (d) to the position shift (p) between the top and the bottom of an interconnect side wall. The traditional definition for the etching factor (the

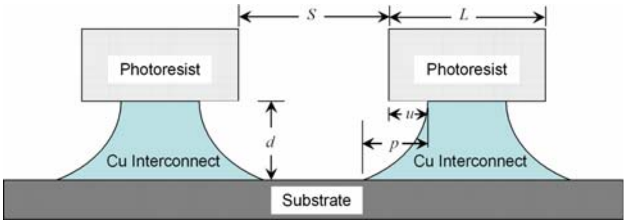


Fig. 1 A schematic diagram of etched copper interconnects on a PCB substrate prior to the removal of the PR mask. The etching factor (E_{ind}) in this work for the side wall of an interconnect is defined as $E_{\mathrm{ind}} = d/p$

ratio of d to the undercut u, as also shown in Fig. 1) is not suitable for current requirements over the interconnects of which the side walls must be as vertical as possible. Short undercuts are actually acceptable provided that the E_{ind} is large enough. The common industrial practice is to over-design the width to accommodate the loss due to expected undercuts. Producing copper interconnects at a relatively large E_{ind} but in a shorter time is essential for modern PCB manufacturing.

Currently available techniques focus on wet chemical etching and may be categorized into two types—immersion etching and spray etching. The immersion etching technique requires that a PCB be fully immersed in a laminar flow field of an etching solution with specifically selected etchants and additives [4–8]. With appropriate flow control, the etching products may be effectively removed from the etched surface, the etching factor be increased, and the etching time reduced. However, due to the isotropic nature of a wet etching process, the E_{ind} of copper interconnects on average is relatively low, and on-line applications would actually yield an even lower E_{ind}. In addition, the etching time is rather long, which is not acceptable for mass production. Although additives may be added to the etching solution as banking agents to promote the E_{ind} in this process, the improvement is usually offset by a longer etching time [8]. The immersion etching process is hardly adopted in the PCB manufacturing industry nowadays. As an alternative, the spray etching technique was developed in the late 1970s. It is currently the most adopted method because it improves the quality of etched interconnects and shortens the etching time [9–14].

Spray etching does not require that the PCB be immersed in the electrolyte. Instead, a PCB is usually placed on a conveyor belt, and the etching solution is directly sprayed on the moving board through particularly designed spray nozzles. These nozzles are located on hollow bars that are positioned in parallel with each other and are filled with electrolyte pumped in through an external pump. The bars together with the conveyor mechanism, the pump and an electrolyte reservoir comprise a spray etching loop system. The time to achieve a preset E_{ind} on the copper interconnects determines the traveling time of the board and the dimension of the spray etching system. The spray etching technique delivers the electrolyte solution to the PCB with an impinging force and thus increase the anisotropy of the etching process [9, 10]. Although the spray etching technique further increases the E_{ind} of copper interconnects to values higher than 5 [9, 11–12], there exists the problem of puddling. Puddles are produced on the top side of a PCB due to horizontally counteracting flows coming from adjacent nozzles and the original etching solution stays at the same spots and prevents fresh etchant from reaching the board surface [9]. This common problem has a serious impact on etching quality and leads to the development of several patching techniques such as swinging nozzles, individual bar pressure control and electrolyte vacuuming. These patching techniques are able to alleviate the puddling problem but lead to more complicated system maintenance. Furthermore, banking agents to improve the etching factor are still used in the spray etching process, but no significant improvements have been reported [12].

For the increasing demand on smaller PCBs for portable electronic devices, conductor patterns of high density are urgently needed. However, currently available etching techniques do not yield copper interconnects of sufficiently high etching factor, and the density of the patterns is therefore limited. For enhancing the mass transfer of the etchant, the use of impinging jet arrays was proposed by Moreno et al. for wet chemical etching of PCBs [15], and a theoretical analysis of mass transfer between the electrolyte from a single jet to a plate was conducted. To effectively promote the etching factor of and avoid the puddles, we employed a modified arrayed jet stream etching system, which allows directed electrolyte streams in ordered arrays to impinge on the conductor pattern of a PCB at a short distance. The objective was to produce copper interconnects of high E_{ind} in a relatively short time without banking agents. The principle and layout of the jet stream etching system are described, and the shape evolution of the etched copper interconnects is presented and discussed.

2 Experimental

A device capable of providing jet streams was designed and fabricated in the shape shown in Fig. 2. The conventional bar type concept as seen in the spray etching system was employed for easy implementation of the new system on currently in-service equipment, but the spraying nozzles on the bar were replaced by a long piece of rectangular parallelepiped with arrayed cone-shaped through holes, as also shown in Fig. 2. The bar had a sealed end and an open end for the electrolyte to enter, and the electrolyte was then

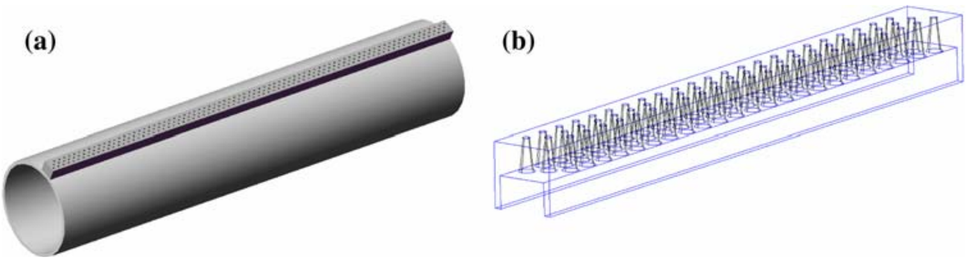


Fig. 2 Schematic diagrams of (**a**) a jet-stream bar with a long piece of rectangular parallelepiped and (**b**) arrayed cone-shaped holes on the rectangular parallelepiped of the bar

released through the cone-shaped holes to create jet streams. The inlet and the outlet of a jet stream hole were 1.0 and 0.5 mm in diameter, respectively, and the pitch among the arrayed holes was 3 mm.

The etching solution used was a commercial grade enchant (MacDermid Inc.) of 45% ferric chloride ($FeCl_3$) mixed with 0.25% ferrous chloride ($FeCl_2$). No banking agents as commonly used in industrial applications were present. To simulate conditions in practical application a dissolved copper concentration of either 104 or 70 g L^{-1} was maintained in the electrolyte prior to each etching process.

A jet-stream etching system, consisting of the jet-stream bar, a sample holder, an etching platform, an electrolyte reservoir, a temperature control device, a diaphragm pump, a flow meter, and a pressure gauge was set up and the system is illustrated in Fig. 3. The etchant was circulated by the pump which also controlled the pressure in the bar and the flow rate of the streams. Upon etching, a patterned PCB sample was placed on the platform underneath the jet-stream bar with the board plane perpendicular to the stream flow direction. The board surface was set at 4 mm from the jet-stream hole outlets. The system temperature was maintained at 53 °C for all etching tests.

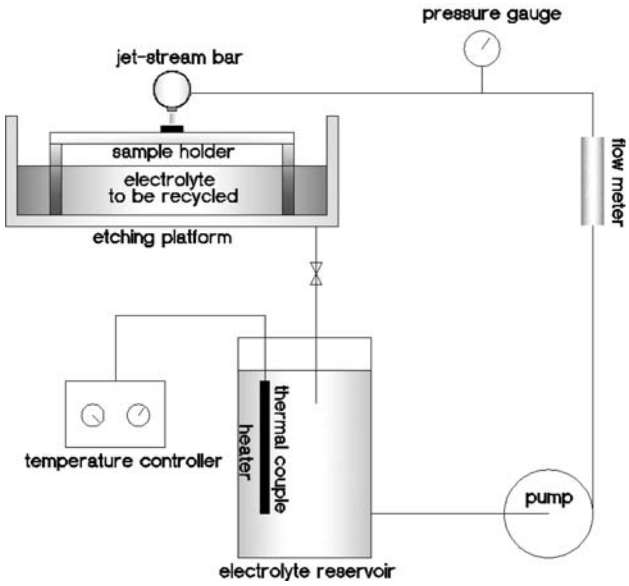


Fig. 3 Schematic diagram of the jet-stream etching system. Note that the PCB sample is not immersed in the etching solution

Flow rates of 80, 70, 50, and 30 L min^{-1} and etching times of 5, 10, and 20 s were adopted to evaluate their impacts on the shape evolution of the copper interconnects. PCB samples with copper foil thickness of 35 μm and PR thickness of 12 μm were machined to a fixed dimension of 2 × 2 cm^2. The interconnect width (*L*) and the spacing (*S*), as defined in Fig. 1, in the patterns of all PCB samples were 140 and 100 μm, respectively.

To demonstrate the uniformity of an etched PCB prepared by the jet-stream etching system and the effectiveness of this system in eliminating puddles, a PCB sample of 30 × 40 cm^2 with copper patterns in *L*/*S* of 140/175 and 140/100 was prepared and etched. The copper foil and PR thickness remained the same. The electrolyte flow rate was set at 50 L min^{-1} and the etching time was 20 s. The dissolved copper concentration was 104 g L^{-1}.

All etched PCB samples were thoroughly cleaned with de-ionized water and dried in air. The samples were then electroplated with a thin gold film at a fixed current of 30 mA for 100 s for easy distinction of the PRs with the underneath copper interconnects and they were sectioned by a low-speed sawing machine before being placed into a scanning electron microscope (SEM, JEOL Model 6330F) for morphological examinations. Etching rates and E_{ind}s for the copper interconnects were derived based upon the dimensions shown in the SEM images. Unless otherwise specified, the examined copper interconnects were the ones lying right beneath the impinging jet steams on the PCB samples. In general, one jet stream could cover the summed width of two adjacent interconnects and the ditch between them.

3 Results and discussion

The effects of dissolved copper concentration and electrolyte flow rate on the shape evolution of the copper interconnects on the PCB samples were evaluated with the jet-stream etching systems. The E_{ind}, which is strongly related to the morphology of a product interconnect, and the etching rate were used to examine the effectiveness of a single etching process.

3.1 Effect of dissolved copper concentration

Two dissolved copper concentrations of 70 and 104 g L^{-1} were selected during the etching process. The flow rate of the etching solution was controlled at 80 L^{-1} min and the etching time was 20 s. The undercuts, E_{ind}s and etching rates on two PCB samples (designated as PC1 and PC2 for etching conditions with 70 and 104 g L^{-1} dissolved copper concentrations, respectively) are summarized in Table 1. At higher dissolved copper concentration, the etching rate was lower and the undercuts were smaller, but the E_{ind}s were relatively larger on sample PC2. The outcome was not surprising in that a higher Baumé (or specific gravity) value of the etching solution would lead to a less aggressive attack on the metal to be etched and would thus promote anisotropy during the etching process and the etching factor [16].

Also listed in Table 1 is the time to exact etching for both samples. This parameter is defined as the time taken for the 35 μm copper foil lying in the open ditch to all be etched away with minimum undercuts. In accordance with the foregoing results, the time to exact etching (8 s) of sample PC1 was shorter than that (12 s) of sample PC2. The times to exact etching of the two samples are all significantly shorter than those by immersion etching and spray etching. In addition, the larger E_{ind}s of 7.0 and 11.7 and etching rates of more than 300 μm min^{-1} in both samples were relatively high in comparison with those reported in the literature on copper interconnects of the same thickness prepared by either immersion etching or spray etching [6, 8, 12].

3.2 Effect of electrolyte flow rate

The flow rate of the electrolyte determined the jet stream impact force on the PCB sample, which in turn determined the anisotropy of the etching. The dissolved copper concentration was maintained at 70 g L^{-1}. Flow rates of 30, 50, 70, and 80 L min^{-1} were adopted, and the physical data of the etched PCB samples (PF1, PF2, PF3, and PC1, respectively) are listed in Table 2. At 30 L min^{-1}, E_{ind}s of 5.0 and 5.8 on the copper interconnect of sample PF1 along with an etching rate of 192 μm min^{-1} were obtained after etching for 20 s. At 50 L min^{-1}, E_{ind}s of sample PF2 were found to increase to 6.8 and 33.0, which signified a breakthrough in wet chemical etching for 35 μm copper foil. In the mean time, the etching rate was markedly increased to 312 μm min^{-1}. Higher flow rates of 70 and 80 L min^{-1} did not yield better etching results in terms of shape evolution but prolonged the undercuts. Figure 4 shows the morphologies of the etched copper interconnects. The etching rates for the two higher flow rates showed no significant difference. Looking at the times to exact etching, we observed that at the lower flow rates of 30 and 50 L min^{-1} it took 15 and 10 s, respectively, to achieve exact etching. Further increases in flow rate to 70 and 80 L min^{-1} did not lead to significantly shorter times. In the current jet-steam etching system, an electrolyte flow rate of 50 L min^{-1} seemed to be the most optimal value in consideration of the magnitudes of the E_{ind}s and the etching rate.

Table 1 Physical data of PCB samples etched at different dissolved copper concentrations

Sample	Dissolved copper concentration (g L^{-1})	Undercut left/right (μm/μm)	E_{ind}^{a} left/right	Etching rate[b] (μm min^{-1})	Time to exact etching (s)
PC1	70	42/28	7.0/4.4	375	8
PC2	104	16/12	11.7/5.8	330	12

[a] E_{ind} is the ratio of the etching depth to the position shift between the top and the bottom of an interconnect side wall

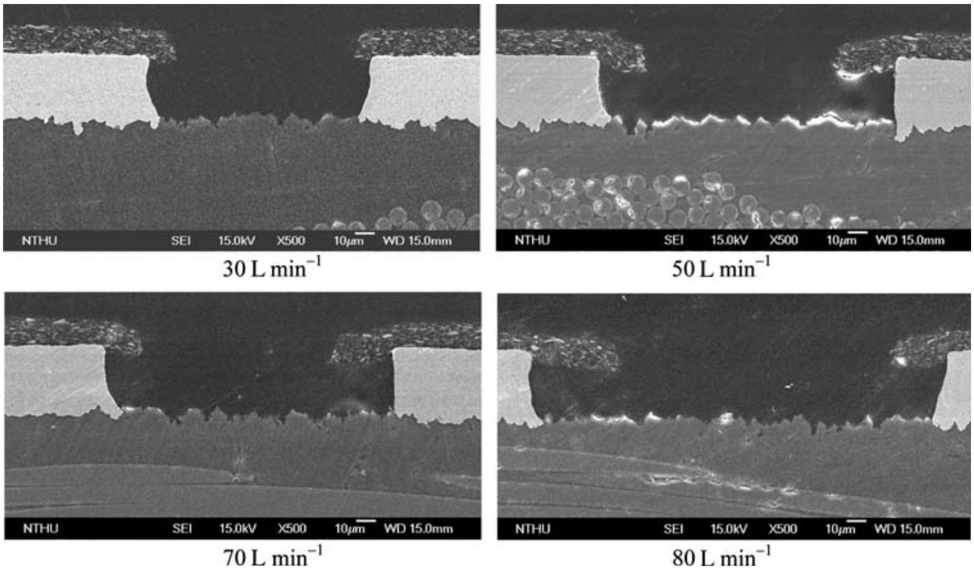
[b] Etching rate was determined by dividing the etched copper depth by an etching time of 4 s, and the total etching time was 20 s. The etching rate was calculated on a 4 s etching time to avoid the influence of over etching that would inadequately distort the actual etching rate

Table 2 Physical data of PCB samples etched at various electrolyte flow rates

Sample	Electrolyte flow rate (L min^{-1})	Undercut left/right (μm/μm)	E_{ind} left/right	Etching rate[a] (μm min^{-1})	Time to exact etching (s)
PF1	30	13/9	5.0/5.8	192	15
PF2	50	23/31	6.8/33.0	312	10
PF3	70	19/32	4.4/35.0	375	8
PC1	80	42/28	7.0/4.4	375	8

[a] Etching rate was determined by dividing the etched copper depth by an etching time of 4 s, and the total etching time was 20 s. Again, the etching rate was calculated on a 4 s etching time to avoid the influence of over etching that would inadequately distort the actual etching rate

Fig. 4 Morphologies of the etched copper interconnects prepared under various electrolyte flow rates of 30, 50, 70 and 80 L min^{-1}



3.3 Uniformity of copper interconnects after etching

Figure 5 shows the etched copper interconnects on a PCB sample of 30 × 40 cm^2. The center line of a jet stream leaving the pressurized bar was directed to impinge on one of the PRs, and the etched copper interconnects were designated as those shown in Fig. 5. The optimal flow rate of 50 L min^{-1} was adopted. To distinguish the shape evolution quality of the interconnects, we defined a shape etching factor (E_{sh}) as the mean value of the two E_{ind}s for the left and right side walls and the results were summarized in Table 3. In the absence of any formulated banking agents to enhance the anisotropy the E_{sh}s of the six interconnects were all found to be greater than 6. Interconnects JL1 and JR1 both exhibited comparatively smaller E_{sh}s of 6.2 and 6.0. Farther away from JC, the E_{sh}s of JR3 and JR4 reached values of greater than 10. The undercuts of the interconnects showed a consistent trend such that, in the same ditch, the undercut confronting the post-impact jet stream flow was larger than the other one due to a locally higher mass transfer rate. This phenomenon was consistent with what had been observed in immersion flow etching at a high linear flow velocity in the board plane direction. Georgiadou et al. [17] showed that the mass transfer

Fig. 5 SEM micrographs showing the etched copper interconnects on a PCB sample and the individual interconnect. A jet stream was directed to impinge on interconnect JC for evaluating the evenness of the jet-stream etching

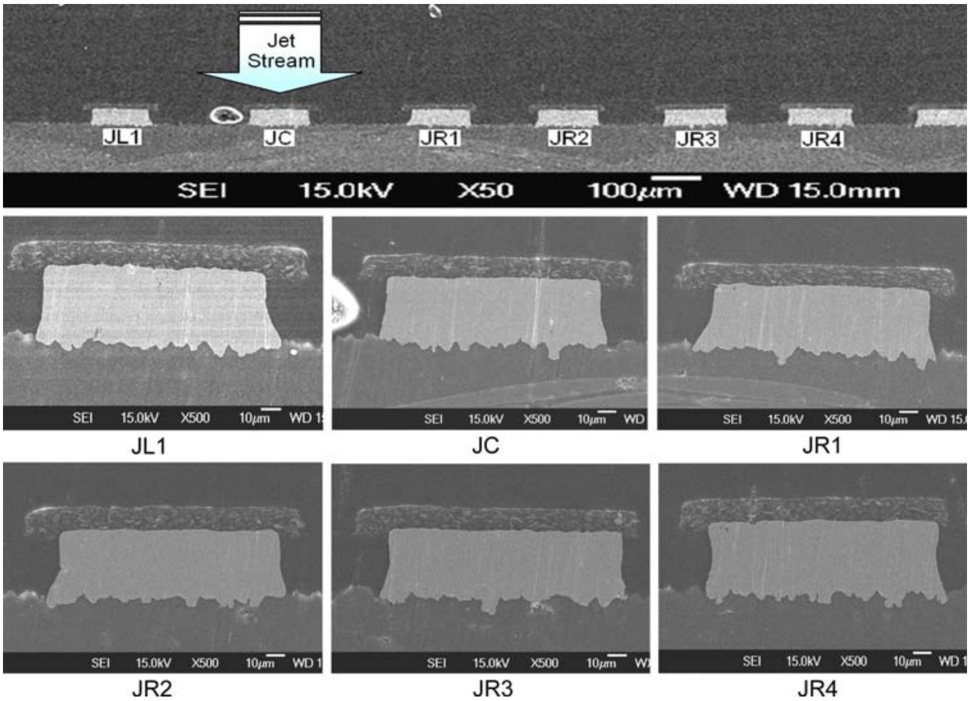


Table 3 Physical data of copper interconnects on an etched PCB sample of 30 × 40 cm^2

Copper interconnect	Undercut left/right (μm/μm)	E_{sh}^{a}
JL1	17/20	6.2
JC	14/16	10.4
JR1	20/12	6.0
JR2	17/13	8.0
JR3	17/8	13.1
JR4	14/4	14.4
JR5	12/6	9.4

[a] The shape etching factor (E_{sh}) of an interconnect is the mean value of the two E_{ind}s for the left and right side walls

distribution in a ditch during immersion flow etching exhibited a single-peak profile with the maximum flux appearing at the downstream end (80% ditch width) where convective transport dominated the mass transport process. Furthermore, the undercuts were all less than 20 μm, and the maximum difference among the undercuts was limited to 16 μm, which is acceptable according to the industrial standard on 140 μm wide interconnects. Another important result to note was that no puddles were observed, and the etchant was seen to constantly flow away from the impact point. For a copper foil thickness of 35 μm, an interconnect width of 140 μm, and a spacing of 100 and 175 μm, we believe that the jet-stream etching system produces promising results at a relatively short etching time of 20 s.

4 Conclusions

A novel wet etching technique for preparing copper interconnects on PCBs is introduced. With the application of a jet-stream etching system, etching factors of interconnects of 35 μm thickness could be significantly increased to values greater than 5 in only 20 s, without the presence of banking agents to enhance the etching anisotropy. A higher dissolved copper concentration led to a lower etching rate as expected. An optimal electrolyte flow rate of 50 L min^{-1} was determined based on the etching factors and undercuts, and higher flow rates did not promote the etching quality. Uniformly etched copper interconnects with shape etching factors of greater than 6 and with undercuts of less than 20 μm were obtained in the current jet-stream etching system suggesting the possibility of practical application of the new system.

Acknowledgements The authors gratefully acknowledge successive funding support from National Science Council of Taiwan under project numbers NSC94-2622-E-007-013-CC3 and NSC96-2622-E-007-007-CC3. Helpful discussion with Prof. Chuen-Horng Tsai is also sincerely acknowledged.

References

1. Kelly J, West AC (1998) J Electrochem Soc 145:3472
2. Georgiadou M, Veyret D (2002) J Electrochem Soc 149:C324
3. Drews TO, Ganley JC, Alkire RC (2003) J Electrochem Soc 150:C325
4. Datta M, Romankiw LT (1989) J Electrochem Soc 136:285C
5. Shin CB, Economou DJ (1989) J Electrochem Soc 136:1997
6. Georgiadou M, Alkire R (1993) J Electrochem Soc 140:1340
7. Bryce C, Berk D (1995) Ind Eng Chem Res 34:1412
8. Papapanayiotou D, DeIigianni H, Alkire R (1998) J Electrochem Soc 145: 3016
9. Kao AS, Stenger HG, Georgakis C et al. (1992) J Electrochem Soc 139:2202
10. Jeong HC, Choi GM, Kim DJ (2007) Int J Precis Eng Manuf 8:73
11. Yamamoto T, Kataoka T, Andresakis J (2001) Circuit World 27:6
12. Shih CW, Wang YY, Wan CC (2003) J Appl Electrochem 33:403
13. Cakir O (2006) J Mater Process Technol 175:63
14. Visser A, Buhlert M (2001) J Mater Process Technol 115:108
15. Moreno OA, Katyl RH, Jones JD,Moschak PA (1993) IBM J Res Develop 37:143
16. Allen DM, Almond HJA (2004) J Mater Process Tech 149:238
17. Georgiadou M, Mohr R, Alkire R (2000) J Electrochem Soc 147:3021