Journal of The Electrochemical Society, **158** (4) H401-H404 (2011) H401
0013-4651/2011/158(4)/H401/4/$28.00 © The Electrochemical Society

Surface Shaping Using Chemical Mechanical Polishing

Purushottam Kumar,*,z Seung-Young Son, Aniruddh Khanna, Jaeseok Lee, and Rajiv K. Singh**

Materials Science and Engineering, University of Florida, 100 Rhines Hall, Gainesville, Florida 32611, USA

In this study we have investigated the phenomena of edge rounding in chemical mechanical polishing (CMP) of patterned surfaces for its potential for creation of different topographies. Hexagonal array of SiO_2 cylindrical pillars with 20 μm diameter, 1 μm spacing and ~1 μm height was polished under different conditions to form rounded surfaces. The effect of CMP variables: pad and pressure were studied by polishing these patterned wafers with Politex and IC1000/Suba IV stacked pad at different pressures. CMP with soft Politex pad led to formation of spherical curvature with radius of curvature dependent on pressure and polishing duration. Radius of curvature as small as 300 μm was obtained at 2.5 psi after polishing for 2 min using Politex pad. The surface evolution dynamics during polishing has been discussed based on contact mechanical model for CMP.
 [DOI: 10.1149/1.3547710]

Manuscript submitted August 18, 2010; revised manuscript received December 13, 2010. Published February 23, 2011.

In the last couple of decades, chemical mechanical polishing (CMP) has grown from a glass polishing technology to a standard IC fabrication technique. Chemical mechanical polishing ensured the miniaturization of integrated circuits by providing an appropriate copper removal technique and also providing flatter wafer surfaces for next generation lithographic tools. CMP is used in both front-end and back-end processes, in shallow trench isolation (STI), interlevel dielectric planarization, local tungsten interconnects, and copper damascene.[1] It is finding application in wafer planarization of nonsilicon semiconductor materials, e.g., wide bandgap semiconductors like SiC, GaN for providing damage free substrates.[2–4] Research and development in CMP has almost totally been toward achieving a better local and global wafer planarity, lower defectivity, and damage-free surface, which are the fundamental needs of the semiconductor industry. Owing to this, chemical mechanical polishing has become synonymous with chemical mechanical planarization. Nonplanarizing phenomenon, such as dishing and edge rounding, are categorized as defects and efforts have been made to reduce or eliminate these defects. In our recent study, we reported the use of CMP for fabrication of microlens arrays.[5] Microlenses are used in numerous applications in optical and optoelectronic systems, e.g., in detector and sensor arrays, optical fiber interconnects, switches, amplifiers, isolators, multiplexers, attenuators, and imaging flat panel display systems and photocopiers.[6] This inherent nonplanarizing nature has the possibility of creating curved surfaces, which would open a new avenue for chemical mechanical polishing, that of a surface shaping process.

The material removal rate during CMP depends on the applied pressure, linear velocity, the characteristic of the polishing medium (pad and slurry) and the wafer material. Among these, applied pressure and properties of the pad are the parameters which affect the contact pressure during CMP. Material removal at any location in the wafer is directly proportional to the contact pressure it experiences.[7] Contact pressure is uniform for a featureless flat wafer, whereas for a wafer with high and low elevation features it varies along the wafer.[8–12] Polishing pad and wafer when brought together under an applied pressure leads to deformation of the pad along the wafer features. The local deformation of the pad determines the local contact pressure and hence the local removal rate. It has been observed that the initial removal rate at the edges/corners of a step feature during chemical mechanical polishing is high leading to rounding of edges. Patrick et al. observed the polishing rate of a step feature (rate of height reduction) to progressively decrease during a CMP process.[8] The decrease in polishing rate was more prominent at the edge of the step and reduced toward the center. It can be inferred that as the corners were progressively rounded, the pressure at the edges decreased, leading to decrease in the polishing rate. The contact pressure was dynamic and changed continuously during polishing with change in the topography of the surface. Chekina et al.[9] and Saxena et al.,[10] based on two-dimensional contact mechanical model for CMP of a step feature, predicted a reduction in variation in contact pressure with the progression of CMP, until a steady state was reached. The surface shape reached equilibrium in their model where further polishing did not change the surface topography.

It is generally agreed that the above phenomena is due to the conformal nature of the polishing pad, and that softer pads lead to more edge rounding than harder pads.[8,9] In literature, various other reasons have been attributed to higher polish rate at the edge of a step feature. Runnels, on his flow based feature scale model reasoned the rounding to occur because of high stress generated at the corners by the flowing slurry.[11] Patrick et al. attributed it to the pressure enhancement at the leading edges of the step feature due to the relative motion of the wafer and pad.[8] Chekina et al. based on contact mechanics model suggested that the high initial contact pressure at the corners due to bending of the pad causes edge rounding.[9] In this work we have studied surface shaping using edge rounding phenomena and the effect of CMP variables on the dynamics of surface evolution. Nonplanarizing aspects of CMP, steady state as well as nonsteady state, can be used to shape surfaces with applications in optoelectronics, tribology, etc.

Experimental

A micron thick plasma enhanced chemical vapor deposition (PECVD) silicon oxide was deposited on 1 in.^{2} coupons of soda lime glass. Silicon dioxide was deposited by flowing nitrous oxide (N_2O) and silane (2% SiH_4/N_2) gases at a flow rate of 1420 and 400 sccm, respectively. The glass coupons were heated to 300°C while the chamber pressure was maintained around 550 mTorr. Power was kept at 60 W at a frequency of 187 kHz for formation of low stress silicon oxide. The SiO_2 layer was patterned using Microposit S1813 photoresist and standard UV photolithography using a Karl Suss MA6 Aligner with a 365 nm Hg i-line radiation. The pattern consisted of hexagonal arrangement of circular dots of 20 μm diameter and 1 μm spacing. The samples were etched in 15 sccm SF_6 and 5 sccm Ar in a Uniaxis Shuttlelock RIE-ICP reactor under 100 W DC and 600 W RF power to form cylindrical pillar-type patterns. Struers Co. TegraPol-35 with TegraForce-5 tabletop polisher was used for polishing the samples at a down pressure of 2.5, 3.6, 5.4, and 8.2 psi. The platen and head were rotating in the same direction at 70 and 30 rpm, respectively. The relative linear velocity between the pad and the wafer was ~0.7 m/s. Two types of pads: Politex (soft) pad and IC1000/Suba IV (hard) stacked pad supplied by Rodel Inc. were used for polishing. SiO_2 slurry with 5 wt. % loading and *p*H 4 made from dilution of Levasil 50cK with nominal particle size of 80 nm was used for polishing. Slurry flow rate of 50 mL/min was used during CMP. The surface was characterized using a Veeco Dimension 3100 atomic force microscopy using contact mode.

* Electrochemical Society Active Member.
** Electrochemical Society Fellow.
z E-mail: purukr@ufl.edu

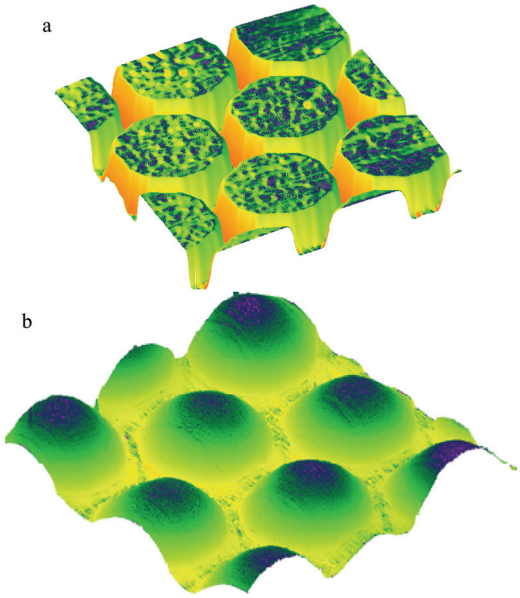

Figure 1. (Color online) AFM image of the surface before and after CMP (a) initial profile before polishing and (b) after polishing with Politex pad for 2 min at 2.5 psi.

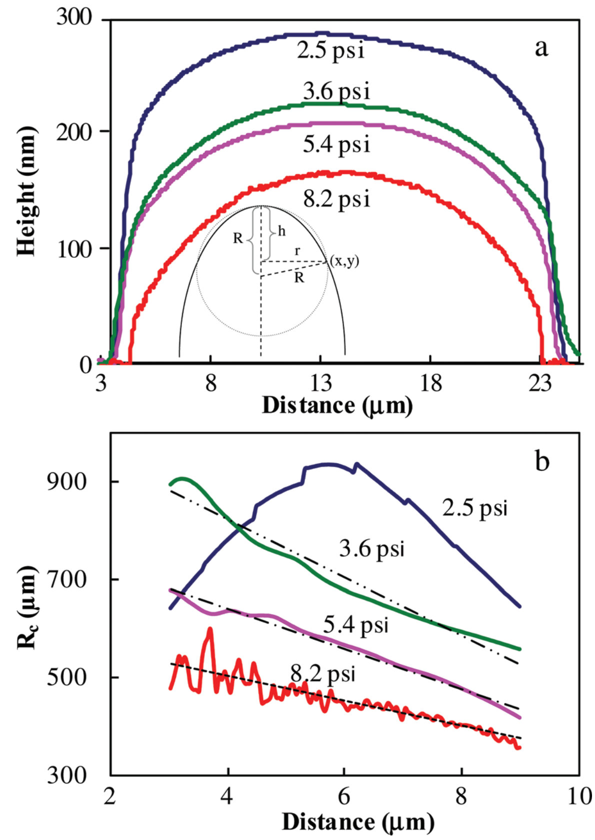

Figure 2. (Color online) Surface profile and corresponding radius of curvature after 1 min of CMP using Politex pad (a) surface profile obtained at different down pressures (b) the corresponding R curves along with the best fit lines.

Results and Discussion

Figure 1a shows the AFM image of initial surface profile of the glass coupons. The cylindrical pillars were of 20 μm diameter and ~700 nm height with interpillar spacing of 1 μm. Figure 1b shows the image of surface after polishing with soft Politex pad for 2 min. The nonplanarizing phenomenon during CMP led to formation of rounded surface profile. CMP of the initial pattern was performed under different conditions to study the effect of CMP variables and the dynamics of surface evolution.

Effect of pressure.—Figure 2a shows the line profile of the feature obtained after 1 min CMP using soft politex pad at different pressures. The line profile was a typical profile obtained under the CMP conditions. Both within an array and from coupon to coupon the variation in height after CMP under similar condition was within 2%. To analyze the nature of surface profiles, parameter R has been defined. It is the radius of the circle passing through the top of the feature and point (x,y) along the profile given by $R = (h^2 + r^2)/2h$. Inset in Fig. 2a shows schematically the representation of R. R is loosely related to the radius of curvature of the profile. The wide variations observed in the differential radius of curvature ($R = (1 + f')^{3/2}/f''$) of the AFM line profiles necessitated the definition of parameter R. The corresponding variation of parameter R along the step for various line profiles is shown in Fig. 2b. For simplicity only one-half of the R versus distance plot is shown. The R values are decreasing outward from the center at all pressures. The decrease in the value of R toward the edge indicates rounding of edges. The anomalous low pressure curve is due to flatness at the top of feature caused by lower polish rate (seen in Fig. 2a). It can be observed that both the slope of best fit line and the R values are decreasing with increase in polishing pressure. At higher polishing pressure the removal rate is higher, the decrease in slope and R value indicates that as more and more material is removed the rounding moves from the edge toward the center.

Figures 3a and 3b shows the line profile and the corresponding R plot after 2 min of polishing with the politex pad. There is a significant difference in the plots compared to that obtained after 1 min of polishing (Figs. 2a and 2b). Significant lateral material removal can be observed in all the profiles with the initial vertical walls mostly polished away. The R curves (Fig. 3b) for profiles obtained for samples polished at low pressures are horizontal where as the R values of profiles at high pressure is increasing away from the center of the feature. The slope of the linear fit to the R curves is decreasing with decrease in pressure till it becomes approximately horizontal at a pressure of less than 5.4 psi indicating a spherical curvature. The horizontal R curve of samples polished at lower pressure is lower than those polished at higher pressures. The spherical surface profiles obtained at lower pressure has smaller radius of curvature than those polished at higher pressures. High pressure polishing would lead to curved surfaces faster but better curvature (smaller radius of curvature) and high aspect ratio structures is obtained at low pressures.

Effect of pad.—Figures 4a and 4b shows the line profile and the R plot of the step feature polished using harder polyurethane IC 1000/Suba IV stacked pad for 2 min at different pressures. The slope of the R curves is negative for profiles obtained at all pressures with surface showing higher curvature at low pressures as evident from decreasing values of R with decrease in pressure. As pointed out in previous studies, softer pads being more conformal lead to more edge rounding than harder pads.[8–10] After 2 min of polishing using hard pad, the R curve shows similarity with 1 min polishing using softer pads with its negative slopes. Also, in contrast to Fig. 3a, the vertical walls remain intact when hard pad is used, only a small portion at the top of the pillar shows some curvature. It is evident that for the purpose of surface shaping a softer pad is more desirable.

Effect of time.—A closer look at Figs. 2b and 3b suggests that the slope of R curves starts with being negative at the start of the polishing process then slowly it becomes horizontal and then switches to being positively sloped. The time required for reaching these different stages varied with pressure. As can be observed, at a high pressure of 8.2 psi the R curve changes the slope within 2 min where as at lower pressures the R curves became horizontal after

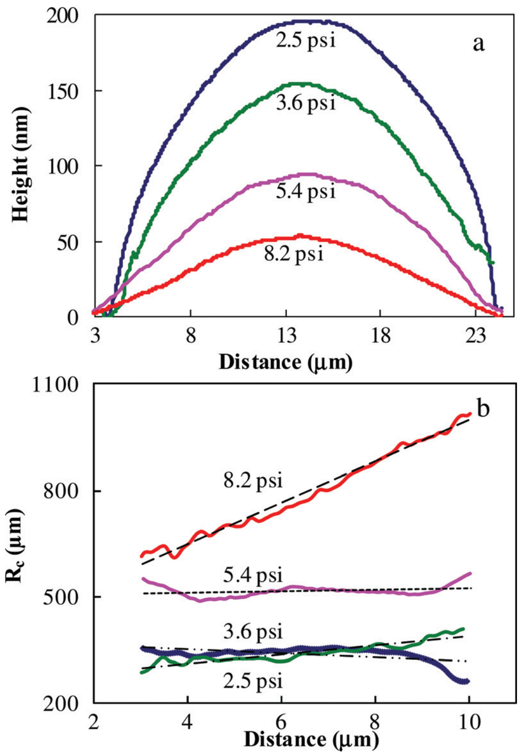

Figure 3. (Color online) Surface profile and corresponding radius of curvature after 2 min of CMP using Politex pad (a) surface profile obtained at different down pressures (b) the corresponding R curves along with the best fit lines.

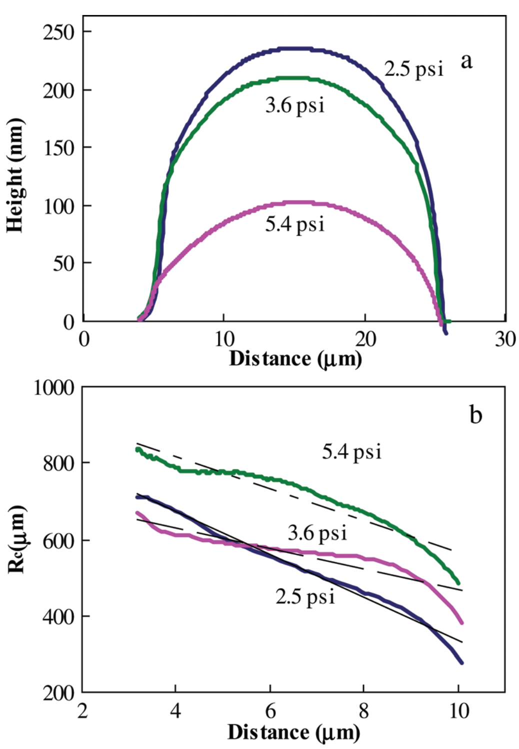

Figure 4. (Color online) Surface profile and corresponding radius of curvature after 2 min of CMP using IC1000/Suba IV stacked pad (a) surface profile obtained at different down pressures (b) the corresponding R curves along with the best fit lines.

2 min. The increase in R value outward is probably because of reduction of step height to an extent where the bottom surface of the step is also being polished. Further polishing in both cases reduced the step height further and eventually led to a smooth surface. The increase in the overall value of R and also the positive slope of R curve of the profile polished at high pressure (8.2 psi) for 2 min using politex pad, indicates toward this planarization of surface after an overpolish. Surface shaping as seen above is more prominent at low pressures with softer pad where as the exact nature of the surface, i.e., the variation of R along the feature (spherical, elliptical) can be controlled by the duration of polishing.

Discussion

Chekina et al. developed a numerical formulation for surface evolution with the progress of CMP based on contact mechanics.[9] According to 2D contact mechanics, the surface displacement of the pad when it is pressed in contact with a rigid wafer with step features is given by

$$w(x) = \frac{-2(1-\nu^2)}{\pi E}\sum_{i=1}^{N}\int_{a_i}^{b_i} p(s)\ln|x-s|ds + \text{Const} \qquad [1]$$

where ν is the Poisson's ratio and E the elastic modulus of the pad, $p(s)$ the contact pressure, a_i, b_i are the boundary points of the contact domain.[9] The surface displacement of the pad when pressed against a step feature is, as expected, dependent on the elastic properties of the pad, its elastic modulus and Poisson's ratio, i.e., the conformal nature of the pad. The model steady state surface profile for a single step can be derived by integrating Eq. 1. At steady state the removal rate at every point of the feature is same which implies a uniform contact pressure [$p(s)$ constant] along the feature. Equation 1 upon integration under constant contact pressure [$p(s)$] gives

$$w(x) = \frac{-2(1-\nu^2)}{\pi E}p^*a\left[\left(1-\frac{x}{a}\right)\ln\left(1-\frac{x}{a}\right)+\frac{x}{a}\ln\left(\frac{x}{a}\right)+\ln a\right] + \text{Const} \qquad [2]$$

where p^* is the contact pressure which is constant throughout the step, a is the width of the step. Figure 5a shows the plot of the function $(y-1)\ln(1-y) - y\ln y$, $0 < y < 1$ for various values of the prefunction coefficient $K([2(1-\nu^2)]/(\pi E)p^*a)$. The prefunction coefficient K, represents the effect of CMP variables: pad properties (elastic modulus and Poisson's ratio), down pressure and pattern width on the surface profile during CMP. Theoretically, the possibility of achieving different steady state profiles for a particular step width by changing the CMP variables can be seen from Fig. 5a. Decrease in the value of K, which can be caused by high elastic modulus (hard pad) or low pressure polishing, reduces the rounding effect. Figure 5b shows the variation of parameter R along the steady state profile for various values of K. When K is low (high elastic modulus of pad, low pressure), R decreases from the center of the step outwards. Higher R in the center region indicates a relatively flatter step polish. For a particular value of K, R is constant throughout, which indicates a spherical curvature. At higher K values (low elastic modulus, high pressure), R is lower at the center indicating a more curved surface at the center of the step. Equation 2 and the prefunction constant can be used to get an insight into the surfaces obtained after polishing with politex and IC1000 pads. In Fig. 2b, the decrease in R values outward from the center after 1 min of polishing using politex pad resembles the curves for lower values of K (Fig. 5b). The lowering of R values at high pressure polishing is consistent with the fact that high K at high pressure gives more curvature. In Fig. 3a the surface after 2 min of polishing at different pressures looks similar to profiles obtained for decreasing values of K (Fig. 5a). This will seem like an anomaly particularly because increase in pressure increases the value of K which is opposite of what the modeled curve depicts. The similarity arises from the high removal rate

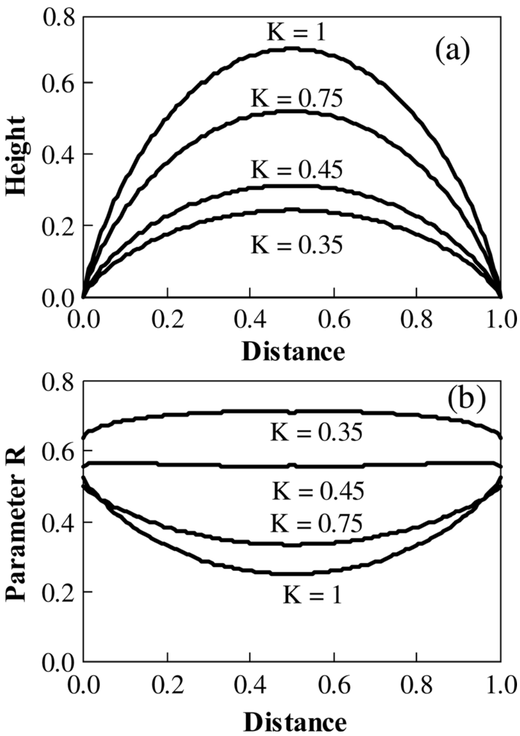

Figure 5. Theoretical steady state curve derived from the contact mechanics model (a) theoretical steady state curves for different values of prefunction coefficient K (b) the corresponding R curves.

at high pressures which has reduced the step height. R plots, which are a better way of comparing the nature of surface profiles, are horizontal at low pressures where as it is increasing outward at high pressures. This is similar to the trend with decreasing value of K shown in Fig. 5b, thus the nature of surface profile is similar to that predicted by the model. The IC1000 pad has higher modulus than the politex pad which gives a lower value of the prefunction coefficient K. Low value of K implies higher R values meaning low curvature surface. It can be observed from Fig. 4b that the R values are comparatively higher when polished with hard pad than that obtained after polishing with politex pad.

The prefunction coefficient K, along with the polishing period determines the surface obtained during CMP. The Poisson's ratio of both the pads is similar ~0.2 where as the elastic modulus of IC1000 pad (29 MPa) is ~sixfold higher than that of Politex pad (5 MPa).[10,12] The K value for Politex will always be ~sixfold larger than IC1000 pad for all pressures and pattern width. The prefunction coefficient (K) for a step width of 20 μm and pressure of 2.5 psi was calculated to be 0.007 and 0.042 for IC1000 and Politex pad, respectively. It should be noted that though the K value of the Politex pad is lower than those plotted in Fig. 5, different curvatures including spherical were attained. Equation 2 is based on two-dimensional contact mechanics. It defines the steady state profile after CMP of a 2D step feature with equal elevated and recess width. The width of recess in a patterned wafer would affect the deformation of the polishing pad and hence would alter the polishing dynamics. Overall, the dynamics of the polishing process, the effect of CMP variables, pad and pressure, seems to follow the modeling trends. The surface, changes throughout polishing and an intermediate state would give the desired surfaces under appropriate CMP conditions.

Conclusions

We studied the nonplanarizing phenomena of edge rounding for creation of surfaces with different curvatures. A softer pad with low elastic modulus at low pressures is most suited for shaping of surfaces. The dynamics of the polishing process seems to follow the contact mechanical modeling trends. The various CMP variables; pad, pressure, affect the profiles as predicted by the modeling work of Chekina et al.[9] Various curvatures including spherical were created by CMP at different stages of polishing. CMP, which till now has been looked at only as a planarization technique, can be used for creating different topographies for applications in tribology, optoelectronics etc.

University of Florida assisted in meeting the publication costs of this article.

References

1. J. M. Steigerwald et al., *Chemical Mechanical Planarization of Microelectronic Materials*, John Wiley & Sons, New York, 1997.
2. X. F. Chen, X. G. Xu, X. B. Hu, J. Li, S. Z. Jiang, L. N. Ning, Y. M. Wang, and M. H. Jiang, *Mater. Sci. Eng. B*, **142**, 28 (2007).
3. X. A Fu, C. A. Zorman, and M. Mehregany, *J. Electrochem. Soc*., 149, G643 (2002).
4. P. R. Tavernier, T. Margalith, L. A. Coldren, S. P. DenBaars, and D. R. Clarke, *Electrochem. Solid State Lett*., 5, G61 (2002).
5. P. Kumar, S. Y. Son, J. Lee, F. C. Chang, A. Khanna, A. C. Arjunan, and R. K. Singh, *Electrochem. Solid State Lett*., 12, H269 (2009).
6. F. T. O'Neill and J. T. Sheridan, *Optik*, **113**, 391 (2002).
7. F. Preston, *J. Soc. Glass Technol*., **11**, 247 (1927).
8. W. J. Patrick, W. L. Guthrie, C. L. Standley, and P. M. Schiable, *J. Electrochem. Soc*., **138**, 1778 (1991).
9. O. G. Chekina and L. M. Keer, *J. Electrochem. Soc*., **145**, 2100 (1998).
10. R. Saxena, D. G. Thakurta, R. J. Gutmann, and W. N. Gill, *Thin Solid Films*, **449**, 192 (2004).
11. S. R. Runnels, *J. Electrochem. Soc*., **141**, 1900 (1994).
12. S. H. Chang, *Microelectron. Eng*., **82**, 136 (2005).