Simple and cost-effective fabrication of size-tunable zinc oxide architectures by multiple size reduction technique

Hyeong-Ho Park¹, Xin Zhang², Seon-Yong Hwang¹, Sang Hyun Jung¹, Semin Kang¹, Hyun-Beom Shin¹, Ho Kwan Kang¹, Hyung-Ho Park³, Ross H Hill² and Chul Ki Ko¹

¹ Patterning Process Department, Nano Process Division, Korea Advanced Nano Fab Center (KANC), Suwon 443–270, Republic of Korea
² 4D Labs and Department of Chemistry, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
³ Department of Materials Science and Engineering, Yonsei University, Seoul 120–749, Republic of Korea

E-mail: hokwan.kang@kanc.re.kr

Received 6 December 2011
Accepted for publication 15 January 2012
Published 2 March 2012
Online at stacks.iop.org/STAM/13/025003

Abstract
We present a simple size reduction technique for fabricating 400 nm zinc oxide (ZnO) architectures using a silicon master containing only microscale architectures. In this approach, the overall fabrication, from the master to the molds and the final ZnO architectures, features cost-effective UV photolithography, instead of electron beam lithography or deep-UV photolithography. A photosensitive Zn-containing sol–gel precursor was used to imprint architectures by direct UV-assisted nanoimprint lithography (UV-NIL). The resulting Zn-containing architectures were then converted to ZnO architectures with reduced feature sizes by thermal annealing at 400 °C for 1 h. The imprinted and annealed ZnO architectures were also used as new masters for the size reduction technique. ZnO pillars of 400 nm diameter were obtained from a silicon master with pillars of 1000 nm diameter by simply repeating the size reduction technique. The photosensitivity and contrast of the Zn-containing precursor were measured as 6.5 J cm⁻² and 16.5, respectively. Interesting complex ZnO patterns, with both microscale pillars and nanoscale holes, were demonstrated by the combination of dose-controlled UV exposure and a two-step UV-NIL.

Keywords: zinc oxide, nanoimprint lithography, size reduction technique, complex patterns

1. Introduction
Simple, fast and cost-effective realization of high-resolution complex patterns of functional materials is crucial in future manufacturing technologies. Zinc oxide (ZnO), a popular functional material, has been widely used in many applications, including high-resolution field emission displays, transparent conducting electrodes, solar cell windows and surface acoustic wave devices [1–5]. Some of these applications require patterned ZnO films as device components. Various methods of patterning ZnO films have been developed to accommodate the trend toward miniaturization of device components. Elaborate nanopatterns are generally fabricated by electron beam lithography (EBL), focused ion beam (FIB) lithography and atomic force microscopy (AFM) nanolithography [6–8]. However, these approaches have limitations in both large-scale production and patterning over large areas, owing to their low throughput, high processing cost and sometimes complicated operational procedures. In contrast, unconventional techniques, such as ultraviolet-assisted nanoimprint lithography (UV-NIL) and many other forms of soft lithography, are simple to operate, cost-effective and suitable for large-area patterning [9, 10]. Since UV-NIL is traditionally used as a one-to-one pattern
replication process, each new imprint pattern requires a new imprint mold and often a new master for the mold. As a result, a large collection of masters and molds is needed for creating different patterns in the UV-NIL, even for a simple rescaling of a pattern. This will increase the fabrication cost substantially, if the masters with high-resolution features are still obtained using costly approaches such as EBL. Therefore, it is necessary to search for a cheaper and more convenient method of generating new nanoimprint masters and molds with finer features.

There is an increasing demand for developing simple, fast and cost-effective fabrication methodologies that integrate the preparation of functional materials and the micro- and nanopatterning of these materials. Micro- and nanopatterning of functional materials such as ZrO$_2$, ZnO and TiO$_2$ using photosensitive organic hybrids have been reported \cite{11-13}. Among various emerging fabrication methodologies, UV-NIL is capable of integrating material preparation and patterning into fewer cost-effective processing steps. In the typical UV-NIL, fabrication of a reliable master with desired architectures is the starting point. For high-resolution UV-NIL, most masters are fabricated by EBL or deep-ultraviolet (DUV) photolithography. This makes high-resolution UV-NIL still partially dependent on expensive lithography technologies, and therefore not easily accessible. One of the promising directions is to start high-resolution UV-NIL with an upscaled pattern produced by UV photolithography, and then find simple and inexpensive ways of reducing feature sizes in the succeeding UV-NIL processing steps. In our previous work, we demonstrated the facile fabrication of both amorphous and crystalline TiO$_2$ and ZrO$_2$ architectures by UV-NIL, using photosensitive metal–organic compounds \cite{14, 15}. It was found that the feature sizes of directly patterned TiO$_2$ and ZrO$_2$ architectures can be reduced by thermal annealing. It would be worthwhile to apply this method to the fabrication of various ZnO patterns, and we anticipated the development of a cost-effective UV-NIL routine that is independent of expensive lithography technologies.

Hill and colleagues extensively researched the use of directly patternable photolithography, called photochemical metal–organic deposition (PMOD), using conventional deep-UV photolithography \cite{16, 17}. However, submicron patterning by PMOD, although seemingly trivial, has not been demonstrated. In this paper, we present a novel technique, which is a modified version of direct UV-NIL for achieving submicron features without the need of masters with submicron features.
In this work, we demonstrate the use of a sequential poly(urethaneacrylate) (PUA) mold replication and inorganic imprinting for the fabrication of various PUA molds and imprinted architectures. Feature sizes are markedly reduced by annealing the imprinted ZnO architectures, and a further reduction can be achieved by repeating the sequential fabrication. This method provides us with a novel size reduction technique without the need to fabricate new masters, as the imprinted and annealed ZnO architectures can be used as masters for making new PUA molds. In addition, dose-controlled UV exposure of the ZnO precursor films was investigated to fabricate complex architectures by a two-step UV-NIL, using PUA molds with microscale holes and nanoscale pillars.

2. Experimental details

2.1. Fabrication of PUA molds and ZnO architectures/masters

The silicon master used for size reduction in this work consists of hexagonal arrays of pillars of 1000 nm diameter and 1300 nm height; it was fabricated by conventional UV photolithography (MA-150 aligner, SUSS MicroTec, Garching, Germany) and subsequent deep reactive ion etching (RIE). Architectures on the silicon master were replicated onto a PUA mold by UV imprinting as described elsewhere [18, 19]. This mold, containing microscale holes, is defined as the first replicated PUA mold. Images of the silicon master and the first replicated PUA mold are shown in figure 1. Prior to use for imprinting, the PUA mold was treated by vapor phase deposition of trichloro(1H, 1H, 2H–2H-perfluorooctyl)silane (97%, Sigma-Aldrich Co.) to improve the release between the PUA mold and the film to be imprinted [20].

The ZnO sol–gel precursor solution was prepared with zinc acetate dihydrate (98%, Sigma-Aldrich Co.), 2-methoxyethanol (99%, Sigma-Aldrich Co.) and monoethanolamine (99%, Sigma-Aldrich Co.) as the starting Zn source, solvent and sol stabilizer, respectively, by a published procedure [21]. Photosensitive 2-nitrobenzaldehyde was also introduced into the solution at a concentration of 0.5 M to improve the photosensitivity. The solution was filtered with a syringe through a 0.45-µm Teflon membrane.

A silicon substrate, p-Si (100) (LG Siltron), was immersed in an acetone bath under sonication for 5 min, followed by an immersion in isopropyl alcohol for 5 min, and then rinsed with deionized water (Milli-Q, Millipore Corp.) for 3 min. The substrate was dried under nitrogen flow and further treated with argon plasma in a plasma cleaner (PDC-002, Harrick Scientific Corp.) for 5 min. The cleaned silicon substrate was treated with an adhesion promoter (Exfix, ZAP-1020, ChemOptics) to enhance the adhesion between the silicon substrate and the spin-coated film. This was accomplished by spin-coating the adhesion promoter onto the silicon substrate at 3000 rpm for 60 s, followed by heating the substrate on a hot plate at 110 °C for 2 min. The thickness of the spin-coated Exfix films was a few tens of angstroms.

A photosensitive precursor film was prepared by spin-coating the ZnO sol–gel precursor solution onto the promoter-treated silicon substrate at 1000 rpm for 60 s. The film was baked on a hot plate at 80 °C for 3 min to remove the residual solvent. The first replicated PUA mold was then pressed against the film at a pressure of 6 bar at room temperature for 3 min, using a NIL-8 imprinter (Obducat, Sweden). Meanwhile, the film was exposed to UV light (25 mW cm−2 with a major wavelength peak of 365 nm) through the PUA mold for 7 min (10.5 J cm−2) to induce photochemical reactions. By detaching the PUA mold from the irradiated film, the first imprinted Zn-containing pattern was obtained. To reduce the feature size, this pattern was annealed at 400 °C for 1 h in air. Images of both the as-imprinted and annealed patterns are shown in figure 1. The annealed ZnO pattern served as a new master to replicate architectures onto a PUA mold, which was used to repeat the above imprinting and annealing steps on a photosensitive precursor film, further reducing the feature size. Figure 1 shows a schematic diagram of the above-described size reduction technique, where the PUA mold fabrication and the

Figure 2. Characteristic photosensitivity curve of the ZnO sol–gel precursor: normalized pattern height remaining after exposure to various doses and rinsing with 2-methoxyethanol for 60 s.

Figure 3. XRD patterns of the UV-irradiated ZnO film and the films annealed at 300, 400, 500 and 600 °C for 1 h.
Figure 4. SEM images of (a) the first replicated PUA mold, (b) the first imprinted pattern and the pattern annealed at 400 °C for (c) 0.5, (d) 1.0 and (e) 1.5 h. 

ZnO sol–gel precursor imprinting and annealing processes are applied twice.

2.2. Fabrication of complex ZnO architectures

To obtain complex ZnO architectures consisting of both microscale and nanoscale features, a second Si master was fabricated using DUV photolithography and subsequent RIE. This Si master consists of hexagonal arrays of holes that are 200 nm deep and 300 nm in diameter. It was used to replicate a PUA mold with nanopillars by UV imprinting [18, 19]. As mentioned in section 2.1, a photosensitive precursor film was prepared by spin-coating the ZnO sol–gel precursor solution onto the promoter-treated silicon substrate at 800 rpm for 60 s, and baked on a hot plate at 80 °C for 3 min to remove the residual solvent. The first replicated PUA mold with microscale holes was then pressed against the film at a pressure of 6 bar at room temperature for 5 min, using a NIL-8 imprinter (Obducat, Sweden). After the film was exposed to UV light for 4 min (6.0 J cm⁻²), the PUA mold with microscale holes was detached. This was followed by another UV-NIL step on the same film, using a PUA mold of nanoscale pillars at a dose of 4.5 J cm⁻² to imprint complex architectures by the combination of dose-controlled UV exposure and a two-step UV-NIL.

2.3. Characterization

Imprinted and annealed Zn-containing architectures were examined using a Hitachi S-4800 field-emission scanning electron microscope (SEM), an FEI Nova 600 Nanolab FIB-SEM, and a PSIA XE-100 atomic force microscope operated in noncontact mode. The crystallinities of UV-irradiated and annealed ZnO films were investigated by x-ray diffraction (XRD) using a Rigaku D/Max 2500 diffractometer with Cu Kα radiation (λ = 1.54178 Å),
operated at 40 kV and 300 mA. To study the photosensitivity and contrast of the ZnO precursor, a set of precursor films were exposed to different doses of UV light during the imprinting. The imprinted patterns were then rinsed with 2-methoxyethanol for 60 s to remove the unconverted component of the film. The height of the resulted patterns was measured by AFM. The sensitivity and contrast were derived from a plot of the normalized pattern height versus the exposure dose, as shown in figure 2. It is worth mentioning that solvent rinsing is unnecessary in the UV-NIL of ZnO architectures. The experiments designed here were used to evaluate the extent of photochemical conversion against exposure dose and to further optimize the fabrication conditions.

3. Results and discussion

The sensitivity and contrast of the photosensitive ZnO precursor are important parameters for the fabrication of ZnO patterns by UV-NIL. To quantify them, a characteristic photosensitivity curve, presenting the normalized pattern height as a function of the exposure dose, was obtained as shown in figure 2. The contrast (γ), a measure of the selectivity between the converted and unconverted portions of a film in the solvent, is defined using following equation [22].

\[ \gamma = \frac{1}{\log[D_1/D_0]} \]  

Here, \( D_0 \) is the minimal dose required to produce a measurable remaining pattern height after rinsing, and \( D_1 \) is the minimal dose required to produce no change in the remaining pattern height after rinsing. \( D_0 \) and \( D_1 \) are normally determined by extrapolating the linear portion of the curve to obtain the dose values (see figure 2) corresponding to 0 and 1.0 normalized pattern height, respectively. The contrast determines the ability of the photosensitive ZnO precursor to reproduce patterns by UV-NIL, when a precursor film is imprinted with a PUA mold and exposed to UV light and then the PUA mold is detached from the irradiated film. A higher contrast implies that the precursor can reproduce patterns of higher resolution. In addition, the sensitivity (\( D_0.5 \)) is defined as the exposure dose required to obtain a 0.5 normalized pattern height after rinsing. A smaller \( D_0.5 \) implies that the material has a higher sensitivity to irradiation. This means that it requires less energy, i.e. a shorter exposure time, to complete the photochemical conversion. From figure 2, the \( D_0.5 \) and \( \gamma \) values of the ZnO precursor were calculated as 6.5 J cm\(^{-2}\) and 16.5, respectively. A recently reported negative-type resist, one of photosensitive poly(benzoxazole)s, has \( D_0.5 = 78 \) mJ cm\(^{-2}\) and \( \gamma = 4.0 \) for 365 nm irradiation (i-line) [23]. Compared with this resist, the photosensitive ZnO sol–gel precursor used here has a much lower sensitivity but a higher contrast. Although a smaller value is preferred, the precursor sensitivity is not a limiting factor in UV-NIL, as the functional materials are prepared in the patterning steps rather than by means of a sacrificial resist. More importantly, approaches are available to improve the sensitivity of a UV-NIL precursor. For example, the ZnO sol–gel precursor \( (D_0.5 = 6.5 \) J cm\(^{-2}\)\) is much more sensitive to the 365 nm irradiation than the Zr-containing metal-organic precursor.
Figure 6. Schematic of the fabrication of ZnO complex architectures by the combination of dose-controlled UV exposure and a two-step UV-NIL.

As demonstrated in our previous work, thermal annealing in air at 400 °C for 1 h is sufficient to convert the imprinted ZrO$_2$ architectures from amorphous phase to crystalline phase. Meanwhile, a substantial volume reduction, originating from the elimination of organic molecules trapped inside the film, densification of materials and structural arrangement for the formation of crystalline phase was observed in the annealed ZrO$_2$ architectures [14]. Similar results are anticipated for the thermal annealing of imprinted ZnO architectures. To study the effects of annealing temperature, ZnO precursor films were prepared on quartz substrates and exposed to UV irradiation under conditions similar to those used for our size reduction technique, followed by annealing at various temperatures. XRD was used to characterize the resultant films and the corresponding XRD patterns are shown in figure 3. As can be seen in figure 3, the irradiated film was amorphous and remained amorphous after annealing at 300 °C for 1 h. For the film irradiated and further annealed at 400 °C, a crystalline ZnO phase corresponding to the hexagonal wurtzite structure appeared, with crystallites of random orientation. At higher annealing temperatures, 500 and 600 °C, the crystallites showed a preferred (002) orientation. This orientation is kinetically favored during the
growth of ZnO films, reflecting the fact that the highest density of Zn atoms is found in the [002] plane [26]. This preference for the (002) plane in wurtzite ZnO films is well known and has been reported for films formed by sputtering, pulsed laser deposition and sol–gel methods [12, 27, 28]. Since annealing at 400 °C is sufficient to produce crystalline ZnO, and higher temperatures simply promote the (002) orientation, we consider 400 °C as the optimal annealing temperature for our size reduction technique.

Figures 4(a) and (b) show SEM images of the first replicated PUA mold and the first imprinted pattern, respectively. The arrays of pillars of 1000 nm diameter and 1300 nm height were successfully replicated by UV-NIL in the imprinted Zn-containing pattern from the silicon master, using the photosensitive ZnO precursor. To study the effects of annealing time, samples of the first imprinted pattern were annealed at 400 °C for 0.5, 1.0 and 1.5 h, and SEM images of the resultant samples are shown in figures 4(c)–(e), respectively. Annealing at 400 °C for 0.5 h reduced the diameter of pillars by 25% (see figure 4(c)), and a larger reduction was observed when extending the annealing time to 1 h. As shown in figure 4(d), the diameter and height of the imprinted pillars became 550 and 600 nm, corresponding to 45 and 54% reductions, respectively. However, no further change in size was observed after annealing for 1.5 h as shown in figure 4(e), indicating that 1 h is sufficient to obtain the maximum achievable reduction.

To obtain smaller ZnO pillars, the PUA mold replication and the ZnO imprinting and annealing processes were repeated, using the first imprinted pattern annealed at 400 °C as a new master. As shown in figure 5(a), the architectures on the new master were replicated onto a PUA mold as a second replicated PUA mold. Figures 5(b) and (c) show SEM images of the second imprinted pattern and the pattern annealed at 400 °C for 1 h. The pillar diameter and height in figure 5(c) are 400 and 300 nm, respectively. Therefore, by applying our size reduction technique twice, the obtained diameter and height of ZnO nanopillars were reduced by 60.0 and 76.9%, respectively, from the pillar dimensions available on the original Si master. It can be seen that the relative shrinking is always less for the diameter than for the height, which could be related to the lateral confinement due to the material’s adhesion to the substrate. Further size reduction is still possible by repeating the above-described size reduction technique. However, to apply the size reduction technique several times, a silicon master with high-aspect-ratio patterns may be needed because of the stronger shrinking in the vertical direction than in the lateral direction. For example, shorter pillars show much less lateral reduction and edge sharpness, which are apparent by comparing the first and second imprinted and annealed patterns. Also, as the size reduction technique is repeated further, the imprinted pattern tends to be more oblique. This tilting can be explained by the rigid lateral confinement from the substrate for the base of pillars, which is reduced for the top of pillars. The obliqueness
of pattern sidewalls is replicated in the next imprinted pattern and becomes more pronounced by a further size reduction. Despite the significant shrinkage, macroscopically uniform and crack-free ZnO nanopillars were obtained on 4 in. wafers with good repeatability.

We have also explored the use of UV-NIL to fabricate complex ZnO architectures. Figure 6 shows a fabrication schematic of complex ZnO architectures by a modified UV-NIL. In this process, the exposure dose during UV-NIL is controlled so that two PUA molds with different architectures can be sequentially imprinted onto one precursor film to form complex architectures. In our previous experiments on size reduction, 10.5 J cm$^{-2}$, a more than sufficient dose, was used to ensure the complete photochemical conversion of the imprinted films. As mentioned above (see figure 2), the sensitivity for the ZnO precursor films was 6.5 J cm$^{-2}$, i.e. they require an exposure of 6.5 J cm$^{-2}$ to obtain about 50% photochemical conversion. However, we found it unnecessary to achieve a 50% photochemical conversion in UV-NIL to imprint architectures, as there is no liquid development required for pattern formation. Architectures were successfully imprinted in a precursor film using a PUA mold of microscale holes and a dose of 6.0 J cm$^{-2}$. This was followed by another UV-NIL step on the same film, using a PUA mold of nanoscale pillars and a dose of 4.5 J cm$^{-2}$. Finally, a complex pattern, containing both microscale pillars and nanoscale holes, was fabricated with well-defined geometry and reasonable pattern fidelity, as shown by the SEM and AFM images in figure 7. The diameters of the resultant microscale pillars and nanoscale holes were 1000 and 300 nm, respectively, the same as those on the Si masters. Interestingly, the pillar height and hole depth were approximately 900 and 150 nm, corresponding to 30.8 and 25.0% reductions, respectively. Presumably, the partial photochemical conversion and double imprinting hindered the reproduction of architecture dimensions in the vertical direction. However, this is not a concern in the UV-NIL approach studied in this work, as all the pattern dimensions will be reduced when annealing of the imprinted patterns is required to obtain architectures of functional materials. Nevertheless, a uniform complex ZnO pattern was obtained using our UV-NIL approach. It can be useful in photovoltaic, photocatalytic and sensing device applications requiring a simple and cost-effective fabrication of complex architectures on surfaces.

4. Conclusions

We have described a novel size reduction technique for the fabrication of ZnO patterns and polymer molds with reduced feature sizes, using masters with large feature sizes that can be prepared by low-cost UV photolithography rather than expensive EBL or DUV photolithography. This method was developed on the basis of the direct UV-NIL of functional materials, where the polymer PUA replication and ZnO imprinting and annealing processes are used sequentially and can be repeated to achieve a smaller feature size. By applying the size reduction technique twice, the diameter and height of the obtained ZnO nanopillars were reduced by 60.0 and 76.9%, respectively, from the pillar dimensions available on the original Si master. Despite this significant shrinkage, macroscopically uniform and crack-free ZnO patterns were obtained on 4 in. wafers. In addition, the fabrication of complex ZnO architectures was demonstrated by the combination of dose-controlled exposure and a two-step UV-NIL using two PUA molds with different architectures. It was found that the photosensitive ZnO sol–gel precursor is suitable for producing functional ZnO architectures by UV-NIL. With appropriate photosensitive precursors, the fabrication of other functional metal oxide architectures is also possible by UV-NIL. Our UV-NIL technique allows the facile size-tunable fabrication of intermediate imprint masters (or molds), as well as the resist-free fabrication of functional oxide patterns. It will be an interesting area of future work to investigate how the feature size and shape of functional oxide patterns can be further tuned by applying various plasma etch technologies.

Acknowledgment

This research was supported by a grant from the Gyeonggi Technology Development Program funded by Gyeonggi Province.

References

[1] Tian Z T, Voigt J A, Liu J, Mckenzie B, Mcdermott M J, Rodriguez M A, Konishi H and Xu H 2003 Nature Mater. 2 821
[2] Saito N, Haneda H, Sekiguchi T, Ohashi N, Sakaguchi I and Koumoto K 2002 Adv. Mater. 14 418
[3] Izaki M and Katayama J 2000 J. Electrochem. Soc. 147 210
[4] Gordillo G 2002 Surf. Rev. Lett. 9 1675
[5] Muthukumar S, Gorla C R, Emanetoglu N W, Liang S and Lu Y 2001 J. Cryst. Growth 225 197
[6] Donthu S, Pan Z, Myers B, Shekhawat G, Wu N and Dravid V 2005 Nano Lett. 5 1710
[7] Kim S-W, Ueda M, Funato M, Fujita S and Fujita S 2005 J. Appl. Phys. 97 104316
[8] He J H, Hsu J H, Wang C W, Lin H N, Chen L J and Wang Z L 2006 J. Phys. Chem. B 110 50
[9] Battaglia C et al 2011 Nano Lett. 11 661
[10] George A, Maijenburg W, Nguyen M D, Mass M G, Blank D H A and Elshof J E T 2011 Langmuir 27 12760
[11] Zhao G, Wang Z and Zhang W 2007 Opt. Eng. 46 023401
[12] Chen Y, Yan F, Zhao G and Wang Z 2011 Appl. Surf. Sci. 257 6817
[13] Segawa H, Inoue S, Osada M and Takeda Y 2011 J. Photochem. Photobiol., A: Chem. 221 232
[14] Park H-H et al 2011 J. Mater. Chem. 21 657
[15] Park H-H et al 2011 Microelectron. Eng. 88 923
[16] Avey A and Hill R H 1996 J. Am. Chem. Soc. 118 237
[17] Zhang X and Hill R H 2006 J. Photopolymer. Sci. Technol. 19 477
[18] Suh K Y, Jeong H E, Kim D-H, Singh R A and Yoon E-S 2006 J. Appl. Phys. 100 34303
[19] Choi S-J, Yoo P J, Baek S I, Kim T W and Lee H H 2004 J. Am. Chem. Soc. 126 7744
[20] Kim J Y, Choi D-G, Jeong J-H and Lee E-S 2008 Appl. Surf. Sci. 254 4793
[21] Kim J Y, Park H-H, Reddy A S, Chang H J, Jeon H, Chang Y and Park H-H 2008 Ceram. Int. 34 1055
[22] Marqués-Hueso J, Abargues R, Canet-Ferrer J, Agouram S, Valdés J L and Martínez-Pastor J P 2010 Langmuir 26 2825
[23] Mizoguchi K, Higashihara T and Ueda M 2009 Macromolecules 42 1024
[24] Hong C-S, Park H-H, Wang S-J, Moon J, Park H-H and Hill R H 2006 Appl. Surf. Sci. 252 7739
[25] Allen J M, Allen S K and Baertschi S W 2000 J. Pharm. Biomed. Anal. 24 167
[26] Amirhaghi S, Craciun V, Craciun D, Elders J and Boyd I W 1994 Microelectron. Eng. 25 321
[27] Cho S 2009 Trans. Electr. Electron. Mater. 10 185
[28] Chen X-C, Zhou J-P, Wang H-Y, Xu P-S and Pan G-Q 2011 Chin. Phys. B 20 096102