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Sloping profile and pattern transfer to silicon by shape-controllable 3-D lithography and ICP

Jin-Wan Jeon *, Jun-Bo Yoon, Koeng Su Lim

Department of Electrical Engineering & Computer Science, Korea Advanced Institute of Science and Technology (KAIST), 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

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Abstract

This paper describes a simple and effective method to fabricate various shapes and profiles of three-dimensional (3-D) silicon microstructures using a shape-controllable 3-D lithography along with dry plasma etching. The first step is to fabricate 3-D photoresist patterns with various slopes and round profiles on a silicon substrate by the shape-controllable 3-D lithography using polymer dispersed liquid crystal (PDLC) films, which is compatible to conventional lithography process. The second step is to transfer the sloping photoresist patterns into the silicon by etching 3-D photoresist molds and the silicon surface through inductively coupled plasma (ICP) process successively. The proposed microfabrication method for 3-D silicon microstructures can be widely applied for silicon lens arrays and silicon solar cells.

Keywords: 3-D silicon microstructure; 3-D lithography; Pattern transfer; Polymer dispersed liquid crystal (PDLC); Inductively coupled plasma (ICP)

1. Introduction

Recently, it is regarded as of major importance to fabricate arbitrary shapes of three-dimensional (3-D) silicon microstructures for various micro-electromechanical systems. A large number of micromachining methods have been demonstrated for the formation 3-D silicon microstructures such as silicon microlenses, silicon solar cells, and so on. These processes can achieve angled sidewalls or surfaces in silicon through wet etching [1,2], curved surfaces in silicon by utilizing reactive ion etching (RIE) lag [3], 3-D silicon structures using gray-scale lithography along with dry anisotropic etching [4], silicon solid immersion lens using RIE with thermal photoresist reflow process [5], 3-D silicon structures including microlenses from microloading effect of RIE [6], silicon microlens mold through isotropic etching of ICP [7], microlens array for solar cells using ion beam milling with thermal photoresist reflow [8], honeycomb surface textures for multicrystalline silicon solar cells [9].

However, these techniques have some drawbacks such as an unconventional process or a restricted shape of 3-D microstructures. Therefore, these cannot be widely applied for the formation of 3-D silicon microstructures. As the need for fabricating 3-D silicon microstructures more freely and easily, fabrication techniques to control the profiles or shapes of 3-D silicon microstructures are required.

In this paper, we have proposed a simple and effective fabrication technique for various profiles and slopes of 3-D silicon microstructures.

2. Principles

A proposed fabrication method for 3-D silicon microstructures consists of the following process steps:

(1) various slopes and profiles of 3-D photoresist microstructure formation on a silicon substrate, applying the shape-controllable 3-D lithography using polymer dispersed liquid crystal (PDLC) films [10];
(2) 3-D sloping profile and pattern transfer to silicon by etching 3-D photoresist molds and the silicon surface successively, applying inductively coupled plasma (ICP) process.

* Corresponding author.
E-mail address: didy@kaist.ac.kr (J.-W. Jeon).

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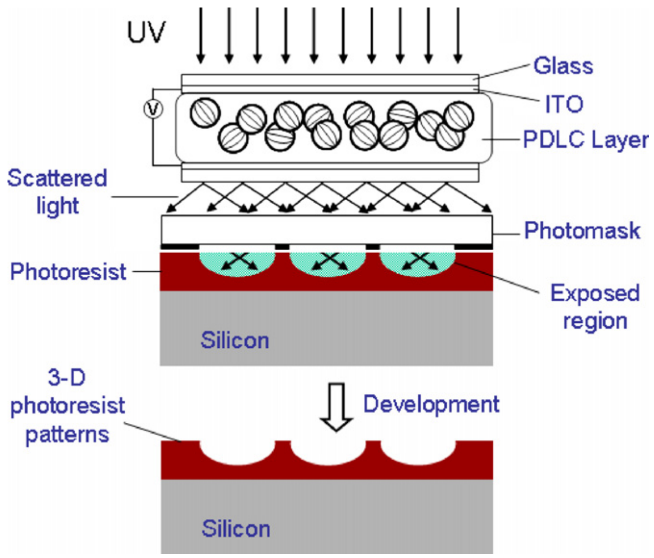

Fig. 1. Schematic views showing the fabrication principles for 3-D photoresist microstructures by 3-D lithography using polymer dispersed liquid crystal (PDLC) films.

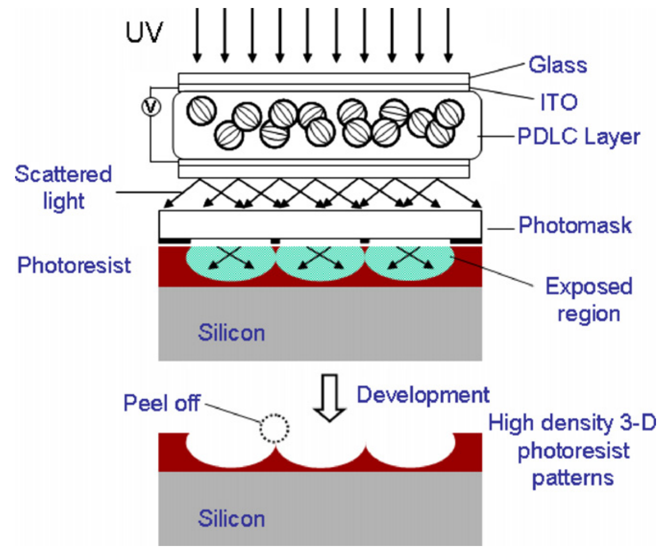

Fig. 2. Schematic views showing the fabrication principles for high density 3-D photoresist microstructures by 3-D lithography using PDLC films.

2.1. 3-D photoresist microstructure formation

Fig. 1 illustrates schematic views of the fabrication principles for 3-D photoresist microstructures by 3-D lithography using PDLC films. The only difference from conventional photolithography is the insertion of the PDLC film on a photomask, which is used as a modulating layer of ultraviolet (UV) directions incident to a thick photoresist layer. UV directions incident to photoresist molds through the PDLC film can be controlled by varying the bias voltage across the PDLC film. The photoresist layer is exposed by UV diffusing rays through the PDLC film and the photomask. By these principles, the photoresist patterns from rectangular to round cross-sections can be obtained after development process. In addition, the slopes of patterned photoresist cross-sections are regulated by the UV exposure time at each bias voltage applied the PDLC layer. By applying this shape-controllable 3-D lithography technique, therefore, various slopes and profiles 3-D photoresist microstructures can be simply and effectively fabricated.

In addition, Fig. 2 illustrates schematic views of the fabrication principles for highly dense 3-D photoresist patterns. By narrowing the spacing between the photomask patterns, the round cross-section of photoresist patterns can be overlapped, and high density 3-D microstructures peeled off the overlapped regions can be formed as shown in Fig. 2.

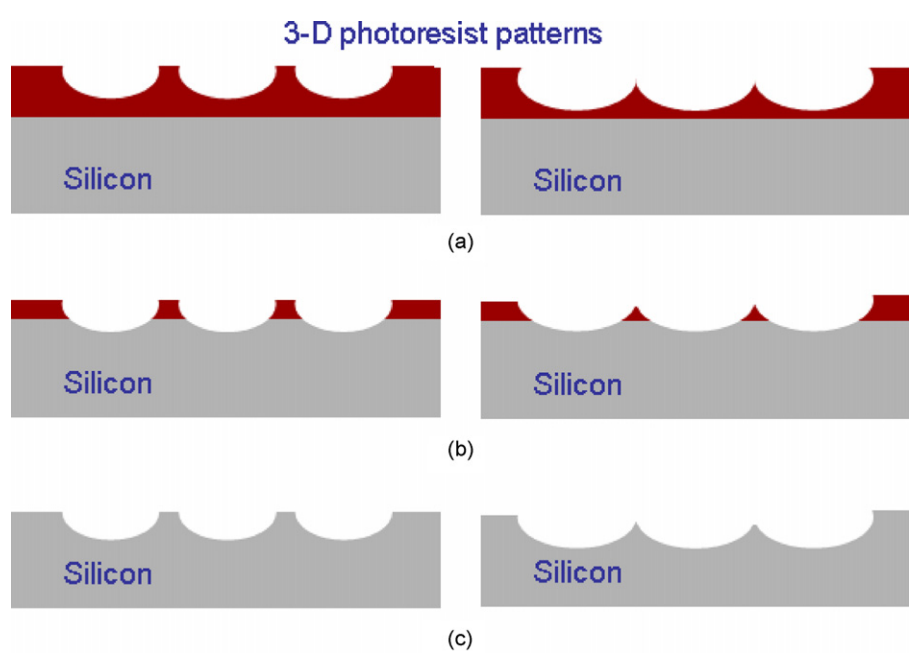

Fig. 3. Process flows of pattern transfer to silicon using ICP etching process: (a) 3-D photoresist patterns on silicon, (b) pattern transfer to silicon during ICP etching process, and (c) 3-D silicon microstructure after ICP etching process.

Hence, various slopes and profiles of 3-D photoresist microstructures can be easily and effectively designed by UV diffusing direction (bias voltage), exposure dose (exposure time), and photomask pattern arrangement. This technique is a very simple and useful one-mask-lithography method compatible to conventional lithography process.

2.2. Sloping profile and pattern transfer to silicon

Fig. 3 illustrates the process flows of pattern transfer method to silicon for 3-D silicon microstructure fabrication. Firstly, 3-D photoresist patterns on the silicon substrate by the 3-D lithography using PDLC films are formed. Next, the 3-D photoresist molds on the silicon are etched using ICP process. The pre-formed photoresist molds on the silicon are used as a 3-D mask in dry anisotropic etching process of silicon surfaces. During ICP etching process, in the region where the photoresist molds are so thin that completely removed prior to others, the 3-D profile or shape of photoresist molds is transferred into the silicon substrate. And, the etching process is stopped after all the photoresist molds are fully removed. Consequently, the pre-formed sloping profiles or shapes of 3-D photoresist microstructures are transferred into the silicon very simply. In addition, the depth or slope of 3-D silicon microstructures can be regulated by the difference in the etching rates of the photoresist and silicon of ICP process.

3. Experimental results

3.1. Process conditions

At the 3-D lithography process, thick AZ9260 photoresist film was used with spin-coating on the silicon substrate at 2000 rpm, 20 s for 10 μm thickness. And thick photoresist layer was soft-baked at 90 °C for 10 min. To prepare the PDLC film, the polymer/liquid crystal Merck TL213 mixture was injected into two glass plates with inner surfaces coated with indium-tin-oxide (ITO) layers. The glass plate thickness was 0.7 mm, and the PDLC layer thickness was measured to be ∼20 μm. Then, the PDLC film is just put on a photomask during the exposure process. The photoresist was UV-exposed through the PDLC and the photomask with varying its bias voltages and expo-

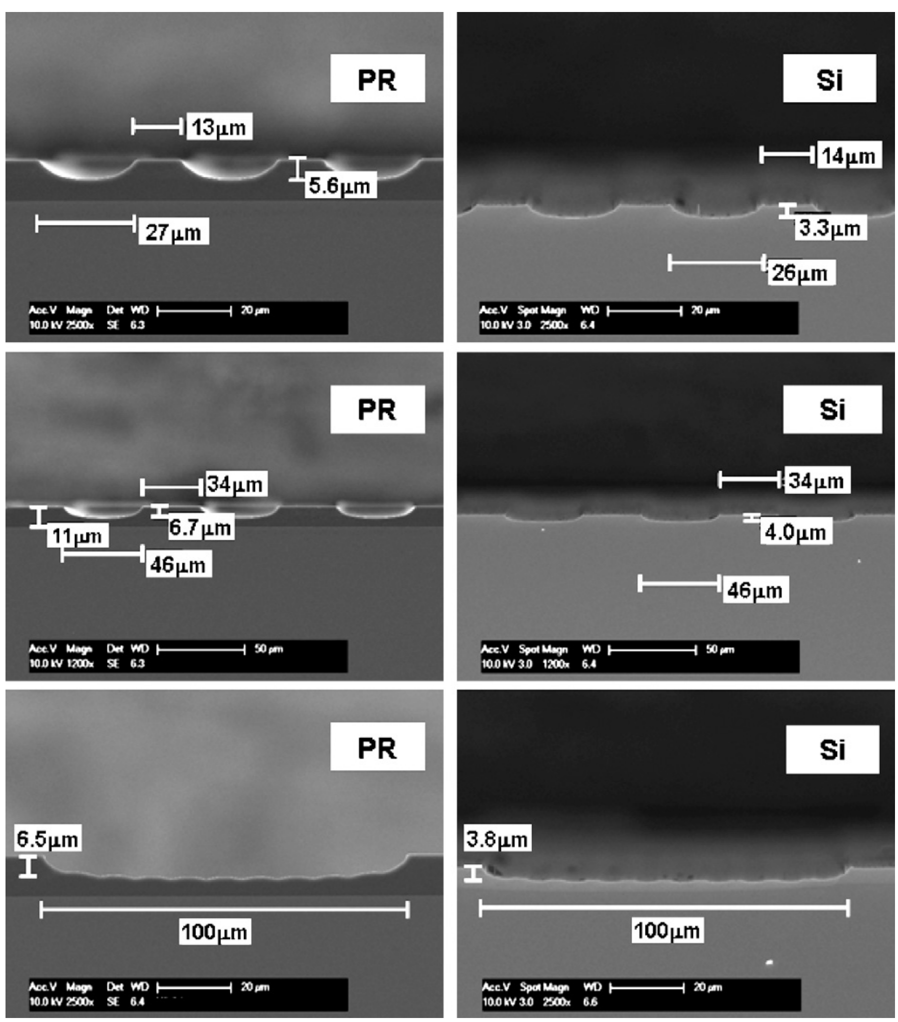

Fig. 4. SEM images of cross-sections of 3-D photoresist microstructures with various sloping profiles acquired by 3-D lithography (left) and 3-D silicon microstructures transferred by ICP etching (right).

sure times. The ICP etching processes for these experiments were performed at the etching conditions of 20 mTorr pressure, $36C_4F_8/14O_2/20Ar$ flows, 1000 W power, 100 V bias voltage, and 25 °C temperature.

3.2. Results and discussion

Fig. 4 shows SEM images of photoresist and silicon microstructure cross-sections fabricated by the proposed methods. The various profiles of 3-D photoresist microstructures in left figures are fabricated by using the aforementioned 3-D lithography process. From each left photoresist pattern, the 3-D silicon microstructure in its corresponding right figure is transferred by using ICP etching process. The photoresist mold is operated as an embedded 3-D mask layer during the etching process. There is no change of width in the structure during ICP process, but the depth of the final silicon structure corresponding to the original depth of the photoresist mold is designed by the relative etching ratio. Consequently, the shape or slope of 3-D silicon surfaces can be controlled for a given targeted 3-D shape by the pre-determined photoresist profile and the relative etching ratio. From the experimental results, the etching selectivity of photoresist to silicon is ∼1.7:1.

Fig. 5(a) shows SEM images of photoresist microstructures applying the 3-D lithography process. By narrowing the space between photomask patterns, these 3-D microstructures are densely formed as described before. The left figure is UV-exposed through the photomask opening patterns of the hexagonal array, and the right is of the orthogonal array. Fig. 5(b) shows SEM images of 3-D silicon microstructures transferred from the photoresist patterns of Fig. 5(a) by applying ICP etching process. And accidental pillars of silicon surfaces are removed by dipping process of wet etchant as shown in Fig. 5(c). As a result, a highly dense 3-D silicon microstructure pattern array is achieved. These textured surfaces in silicon are widely used for silicon microlens arrays and silicon solar cells.

Fig. 6 shows SEM images of various slopes and shapes of 3-D silicon microstructures. According to the pre-determined sloping profiles or shapes of 3-D photoresist molds by using the shape-controllable 3-D lithography process, 3-D microstructures transferred into silicon surface are determined. The photomask used to fabricate the silicon microstructures of

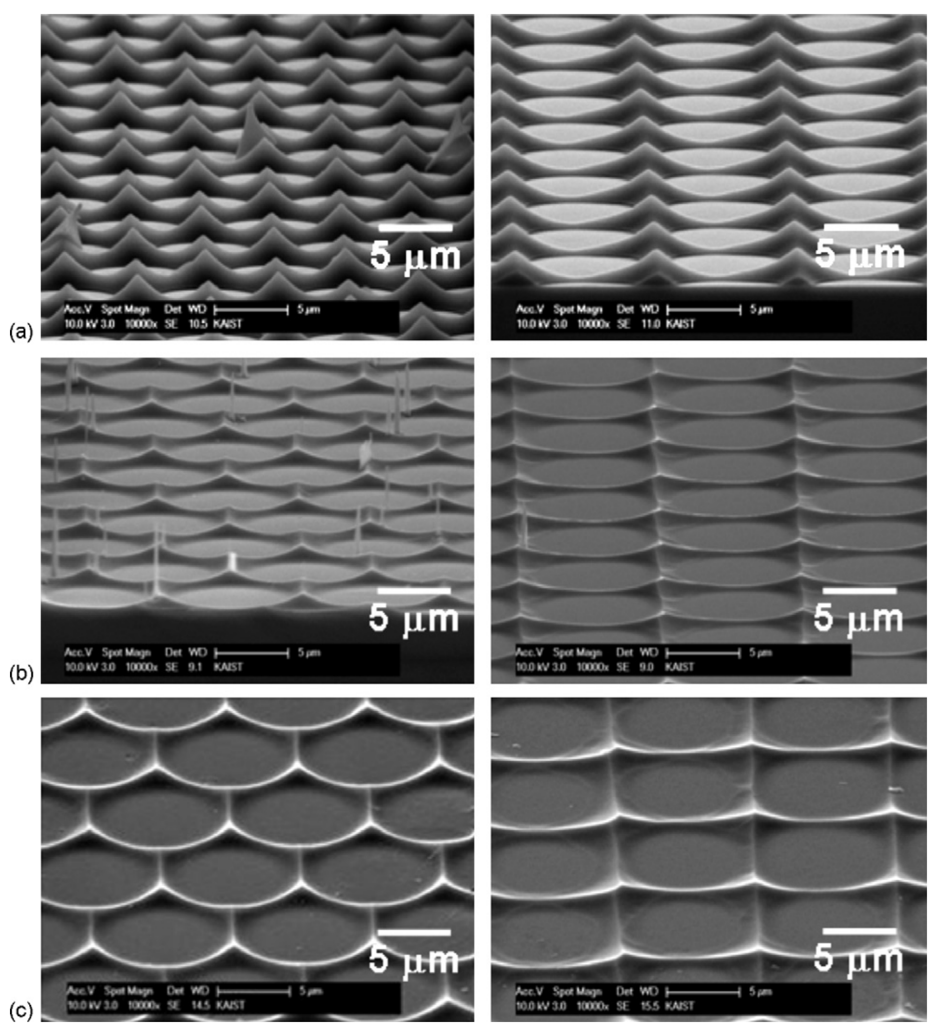

Fig. 5. SEM images of (a) 3-D photoresist microstructures on a silicon substrate by 3-D lithography, (b) 3-D silicon microstructures by ICP etching process, and (c) 3-D silicon microstructures by dipping process with wet-etchant.

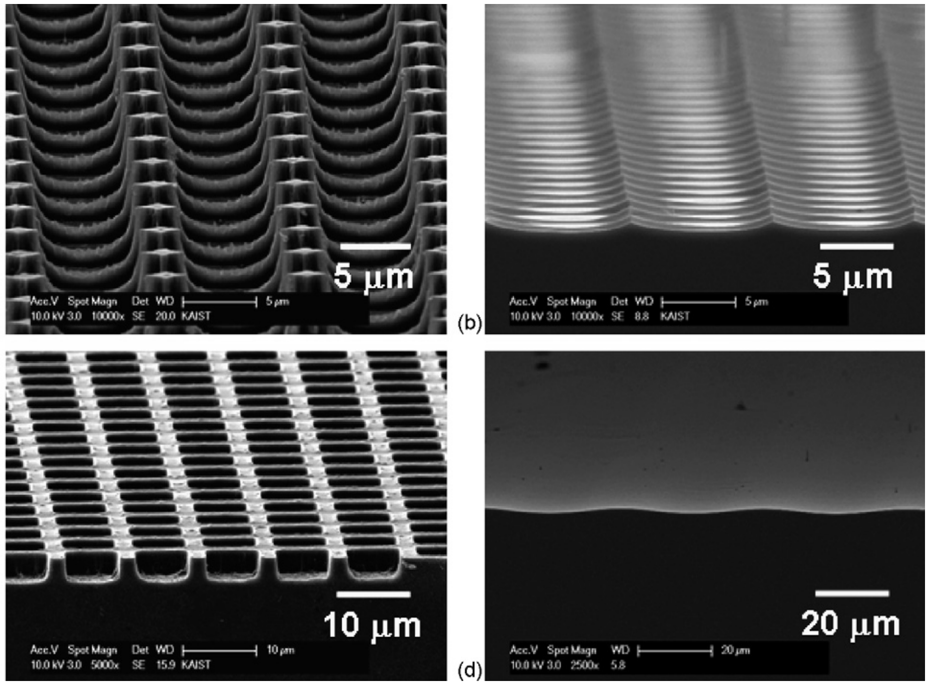

Fig. 6. (a–d) SEM images of various shapes or slopes of 3-D silicon microstructures.

Fig. 6(a and b) consists of circular open patterns in an orthogonal array, and the pitch of the arrays is 10 μm. The UV exposure dose is H-line 560 mJ/cm^2, and the bias voltage of the PDLC is 4 V. However, the diameter of the circular open patterns of Fig. 6(a or b) is 6 or 9 μm, respectively. In the case of Fig. 6(b), the round cross-section of photoresist patterns are overlapped, because the spacing between the patterns is very narrow. As a result, the round shapes of photoresist patterns and transferred silicon patterns are gentler than the cases of Fig. 6(a). The photomask of Fig. 6(c) consists of square patterns in an orthogonal array. The open width is 7 μm, and the pitch is 10 μm. The UV exposure dose is H-line 270 mJ/cm^2, and the bias voltage of the PDLC is 7 V. The slope of transferred silicon microstructures is very steep because the diffusing rate of the PDLC is low at the bias voltage of 7 V. The photomask of Fig. 6(d) consists of one-dimensional line pattern array. The open or closed width of mask patterns is 20 or 20 μm, respectively. The UV exposure dose is H-line 760 mJ/cm^2, and the bias voltage of the PDLC is 4 V. In this case, the 3-D silicon microstructures have very gentle slopes. These fabrication results have been shown to control the sloping profiles of 3-D silicon surface using photomask pattern arrangements, bias voltages of the PDLC film, and UV exposure doses.

4. Conclusions

We have developed a new fabrication method for 3-D silicon microstructures. This method for sloping profile and pattern transfer to silicon is to combine the shape-controllable 3-D lithography using PDLC films with ICP etching process. Applying this 3-D lithography, very different slopes and profiles of 3-D photoresist microstructure are simply fabricated. And 3-D silicon microstructures are transferred from these photoresist structures during anisotropic etching process. This is an easy and effective method to fabricate more various slopes and profiles of 3-D silicon microstructures. This fabrication method for 3-D silicon microstructures can be utilized wide applications such as silicon microlens arrays, and silicon solar cells with textured surfaces.

Acknowledgements

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Biographies

Jin-Wan Jeon received the BS, MS, and PhD degrees in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1997, 1999, and 2005, respectively. His doctoral research concerned the development of digital micromirror devices for display applications. He is currently a post-doctoral research engineer in the Department of Electrical Engineering, KAIST. His research interests include 3D micro- and nano-fabrication technologies, and 3D MEMS for optical/display devices.

Jun-Bo Yoon received the BS (*summa cum laude*), MS, and PhD degrees in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1993, 1995, and 1999, respectively. His doctoral research concerned the development of the three-dimensional microstructure technology (3D MEMS) for microfluidic systems and integrated inductors. From 1999 to 2000, he was with The University of Michigan at Ann Arbor, as a post-doctoral research fellow, where he demonstrated a movable dielectric tunable micromechanical capacitor for RF applications. In 2000, he returned as a research assistant professor to the Department of Electrical Engineering, KAIST, where he is currently an associate professor. His research interests include 3D micro–nano structures process technologies, 3D MEMS for wireless communications, and 3D MEMS for optical/display devices. He holds 13 domestic and 13 international patents. He was the recipient of the Third-Place Award of the Student Paper Competition presented at the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS) in June 1999. He received the Department's and University's Excellent Teaching Awards in 2003 and 2006, respectively.

Koeng Su Lim received BS degree in electrical engineering and MS degree in energy materials engineering from Yokohama National University, Japan, in 1977 and 1979, respectively, and received a PhD degree in physical electronics from Tokyo Institute of Technology (TIT), Japan, in 1984. He was a researcher at Anritsu Electric Co., Japan, in 1984. From 1984 to 1988, he was an assistant professor in the Department of Electrical Engineering and Computer Science at Korea Institute of Technology (KIT). He joined Korea Advanced Institute of Science and Technology (KAIST) in 1988 as an associate professor in the Department of Electrical Engineering, where he is currently a professor. His research interests include a-Si:H based solar cells, nano-floating gate memory devices, and optical/display devices. He holds 12 domestic and 9 international patents.