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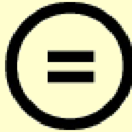

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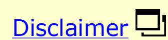

석사학위논문

소프트 몰드 연신을 통한 나노패턴의 모양과 배열의 제어

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이 논문을 공학석사학위논문으로 제출함

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Abstract

Manipulation in Shape and Arrangement of Nano Pattern Using Stretched Soft Molds

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Various methods for soft lithography have been developed due to the temporal and economical limitations of photo lithography, and still a lot of lithographical methods are being developed and studied to apply to different scientific fields. Here, we focus on nano-scale anisotropic patterns formed from a replica molding with curable polymers. We fabricate a stamp having an array of the patterns newly formed from a hexagonal pattern of tens of nanometers composed of dot-shaped vertices. We could successfully transform the dot-patterned feature to an ellipsoidal one and also manipulate

its aspect ratio as desired. Furthermore, we were able to stretch the hexagonal pattern while keeping the dot shape the same, so we came up with a new pattern arrangement. Ultimately, we can notice the change in wetting property of materials having anisotropic structures.

Keywords : stretching, anodic aluminum oxide, ellipsoid, poly(dimethylsiloaxane), anisotropic wetting, hexagonal

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1 Introduction

1.1 Soft Lithography

Fabrication of small patterns is beneficial at information technology industry as it makes possible for more elements per chip, higher performance and lower power consumption. As the structures become smaller, those characteristics get stronger. Generation of small structures might be the same with making patterns on the surface of something. Photolithography is a usual method to create patterns by light injections[2]. A pattern resolution(R) follows Rayleigh Equation that R is proportional to a wavelength(λ) of injected light and NA is numerical at of the lens system, k1 a constant depended on the photoresist[3].

$$\mathrm{R} = \frac{k_1 \lambda}{NA}$$

Since infra structures and technology for light source for short wave length is highly cost, fabrication of high-resolution patterns (under a hundreds nanometers) has been very expensive.[4] Non-photolithographic methods have been developed to overcome limits of conventional photolithography. [2, 4]

Soft lithography is non-photolithographic methods using elastomeric stamps or molds and pattern is transferred to soft substrates.[4] Various techniques have been researched and applied to different kinds of materials according to each property. Soft lithography has a special advantage distinguished from the conventional photolithography. Patterning on flexible substrates and 3D structure is possible without difficulty. Widely used material is Poly(dimethylsiloxane) (PDMS) due to its low interfacial free energy (~21.6 dyn/cm), good chemical stability, good thermal stability and optical transparency (~300nm) and durability of cured PDMS.[2] Owing to low glass transition temperature, PDMS is liquid at room temperature and easily solidify by heating.[2] The cured PDMS is an elastomer deformed easily as stretched or compressed.[2]

1.2 Patterning based on mechanical stress

Mechanical stress on flexible molds is a method that fabricates various patterns (asymmetrical shape) from one single pattern. This was used to reduce the pattern size(width of gratings) under micrometer scale in 1995s.[5] From that time mechanical treatments, bending, compressing and stretching, have been utilize widely for control of shape and size of patterns. Various pattern shapes such as line[5-7], pore[8, 9] and hemisphere[10, 11] were used for change theirs shapes and size. In case of hemisphere patterns, initial pattern size(diameter) was 470 nm and stretched until final pattern sizes increased up to 1 ㎛ at long axis diameters[11]. In addition to inducing the shape and size change, particles were fabricated by filling polymer in pores of ellipsoidal patterns[8]. The aspect ratio of this research reached maximum value 52 by three- times repeated elongations. When liquid vaporize in particles and liquid mixture, anisotropic particles act differently with isotropic ones to relieve coffee ring effect[12]. These asymmetric particles are fabricated by stretching matrixes that contain circle polymer particle at high temperature[13].

And these elliptical patterns have physical properties such as anisotropic optical property and anisotropic wettability. If periodicity of the structure is comparable with light wavelength, the

optical property is affected by surface morphologies[14]. With single-resolved mirror reflective spectra, anisotropic optical reflectivity was characterized and the results presented that peak value of spectrum at long axis of ellipsoids is higher than that at short axis of patterns[10]. Also, asymmetric morphologies lead directional wetting behavior. This behavior was analyzed base on the anisotropic wettability at groove surface[10]. Because of energy barrier difference of two orthogonal directions, contact angle at long axis of elliptical patterns is larger than contact angle at short axis[1]. To maximize this effect, metal coating on one side pave the way to fabricate Janus structures[10].

1.3 Sub−100 nm scale pattern

As science and technologies develop, demand for high degree of accumulation on a chip rises. However, researches that using the stretching molds are limited over hundreds nanometer sizes. A method that applying pressure on stamp and transferring patterns is imprint and this has possibility that make fine structures.[15] Step and flash method in imprint lithography accomplished 60 nm width line patterns[16]. Imprint lithography using hard molds enables to make 10 nm features as well[15]. However physical methods have limitation to solve loading high pressure on molds. The other approach is materials for improving pattern resolution. A required property of the materials for fine pattern replication is high elastic modulus and good wettability. There was a composite that have both stiff layer and flexible layer generating 50 nm features called hard PDMS[17]. Ultraviolet (UV) curable chemical, Polyurethaneacrylate (PUA) with elastic modulus 40MPa is widely used to replicate fine patterns (sub−100 nm) due to its property that enough stiffness and easy releasing[15]. However cured PUA pattern is not enough to deform so that the cured PUA is not suitable to use as stretching molds.

Applying stretching strategy, flexibility of PDMS is appropriate. As mentioned above low elastic modulus and high viscosity of

PDMS prohibit replicating fine patterns. In order to overcome this limitation dilution of PDMS with toluene enhance wettability into the fine patterns. If ratio of toluene to PDMS is higher, more PDMS permeates pattern deeply. Diameter 50 nm dot pattern could replicate by this method[18].

1.4 Purpose of this study

Purpose of this study is economical and time efficient fabrications of sub-100nm patterns with have various shapes and arrangements. Deformation of existing pattern is a key point so flexible patterning material plays an important role. The most popular material was PDMS due to its elasticity. And the sizes of features in these studies were several tens of nanometers which was probably the smallest size that could distinguish between features and features. If small sized (under 100nm) pattern transfer was possible through PDMS, this would have been the most suitable chemicals to achieve the goal. However it was reported that PDMS and toluene mixture increases wettability of PDMS for the patterns, at least 50nm pattern could be replicated perfectly[18]. Using anodized aluminum oxide (AAO) as master mold for patterning could lessen the cost and save the time. The self-assembled AAO has been utilized as nano template ranging from 25nm to 500nm pore packing as hexagonal[19-21]. With controlling applied voltage and reaction time, pore scales are decided. Both positive and negative pattern can be developed through repeating pattern transfers. These stretched molds have anisotropic structures (ellipsoid shapes and elliptical arranges) leading anisotropic properties. Especially, directional wetting behavior was studied.

2 Experimentals

2.1 Fabrication of the AAO Mold

Master mold for nano-scaled pattern is fabricated by anodized aluminum oxide (AAO). Aluminum sheet (99.999%,Goodfellow) is prepared and electric field 40V was applied to this sheet at 15℃ in 0.1M Oxalic acid solution. This process is repeated two times for well-ordered pore array. At 1st anodization, oxide layer growth continues for 12hours and this layer is removed by chromic acid and hydrochloric acid mixture solution at 65℃. Because 1st step is for remaining hexagonal arrangement pits on the aluminum. At the same condition, hexagonally packed embossed aluminum is anodized for few minutes. Pore-widening process at 30℃, 0.1M phosphoric acid was needed to control a pore diameter. (Figure1)

2.2 Patterning

2.2.1 PUA stamp

Replication of AAO and stretched PDMS is done by UV-curable polymer, Poly (urethane acrylate) (PUA, 311RM, Minuta Tech.). Before stamping the AAO, surface of this was modified hydrophobic to easily separate PUA stamp from the AAO with anchoring monoglycidyl ether-terminated poly(dimethylsiloxane) (PDMS,M n

= 5000, Aldrich). When the PUA stamp is made from PDMS mold, the surface modification is not needed due to very low surface energy of PDMS. In order to fabricate PUA stamp, a few droplets of PUA (liquid phase) is dropped on the top of master mold (AAO or PDMS) and Poly(ethylene terephthalate) (PET) film is placed on the PUA droplets.

When the liquid PUA cover whole surface of the mold, this stamping stack is exposed to UV light (λ : 356±20nm, MT-GJ20 Minuta Tech) to cure the PUA for few seconds in case of the AAO mold(for PDMS mold, a few decades of minutes). After curing ends, the PUA stamp was released from master mold and 2nd UV curing continued for 12 hours. (Figure 2)

2.2.2 Nano patterned PDMS molds

Toluene is added to PDMS mixture (prepolymer : curing agent=12.5:1, Slygard 184, Dow Corning) with 3 to 1 ratio (toluene is more than PDMS mixture). This is dropped on the mold (PUA pattern or AAO with modified surface) and let toluene evaporate itself in the air and then toluene-free PDMS is poured on top of that. The curing was for one hour at 80℃ in the air. (Figure 3)

2.2.3 Pore elongation

Pore elongated experimental processor is described at right side of Figure 4 stated from the AAO mold. In order to make stretchable pore pattern, above all rod structure was obtained by replication of the AAO with UV-curable Poly(urethane acrylate)(PUA, 311RM, Minuta Tech). On the rod pattern, PDMS (prepolymer to curing agent was 12.5 to 1 by weight, Sylgard 184, Dow Corning) and toluene mixture was poured and toluene was perfectly removed by natural evaporation in the air. If toluene is remained, PDMS pattern gets relatively big holes overall. Toluene-free PDMS was placed as upper layer of previous PDMS because easy to handle thickness was needed. Gently removed the patterned PDMS was held at stretching tool and elongated as long as preferred length. It was not possible to take images at stretched situations and so the opposite configuration was got through the PUA stamping. The nano-patterned PDMS was reusable to make differently pulled length applied samples owing to perfect recovery of PDMS and absolute replication from them. Detailed explanations about fabrication of the AAO, PUA stamping and small sized PDMS patterning are taken at Supporting Information. (Figure 4)

2.2.4 Rod elongation

A difference with the pore system was direct molding by PDMS from the master stamp AAO. Next processors are the same as those of pore stretching, PUA stamping in order. (Figure 4)

2.3 Characterization

To observe the generated nano patterns, scanning electron microscope (SEM, JSM-6701F, JEOL) and atomic force microscope(AFM, Nanonavi). AAO and PUA pattern were investigated by SEM (electron energy 10 kV) with sputter-coated Platinum and PDMS pattern were done by AFM. Sub -100 nm size patterned PDMS is easily degradable with the SEM electron energy. Anisotropic wetting property is measured by drop shape analyzer (DSA 100, KRüSS). The drop is 1 ㎕ of water and measurement was repeated five times for each sample.

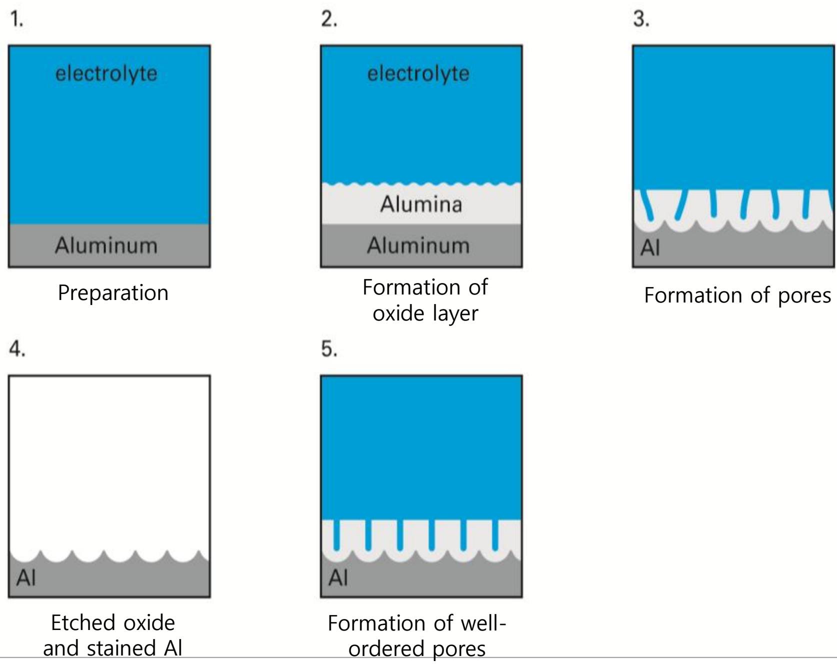


Figure 1. Fabricating steps for anodized aluminum oxide.

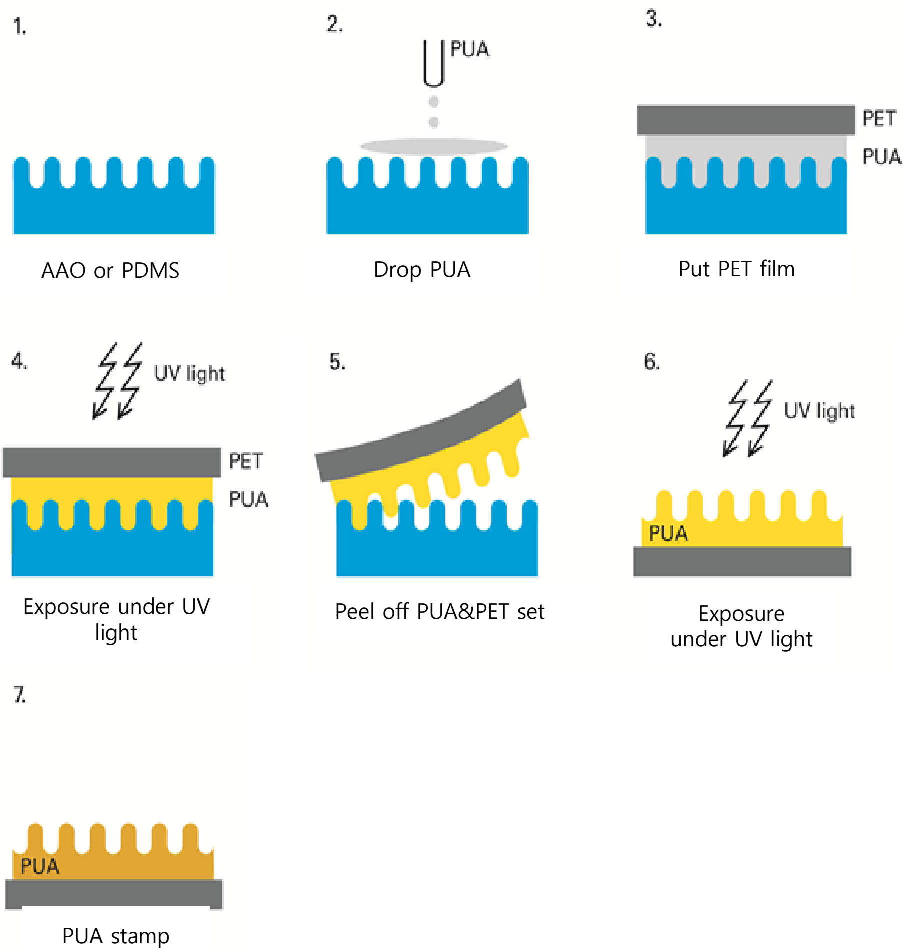


Figure 2. Fabricating steps for PUA stamps.

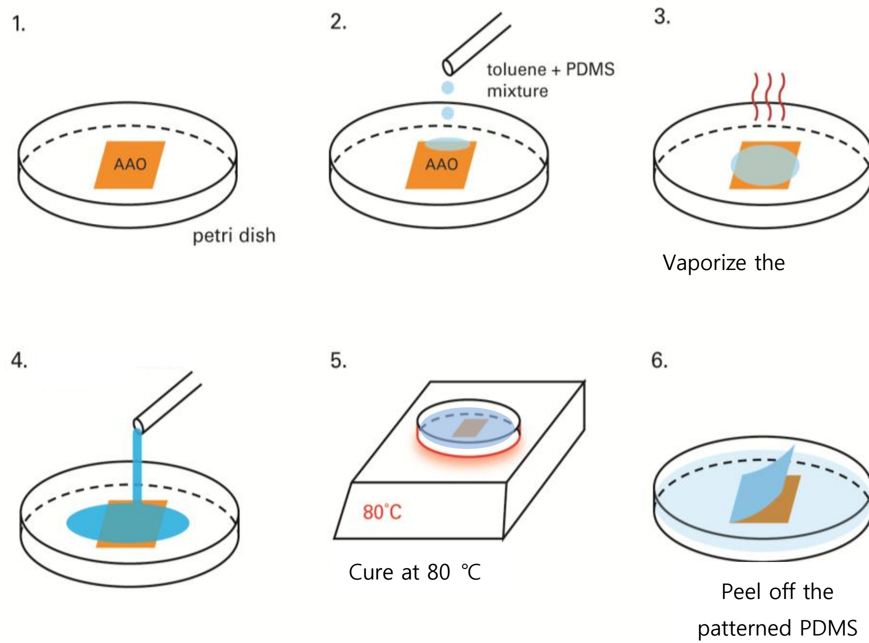


Figure 3. Fabricating steps for sun−100 nm patterned PDMS molds

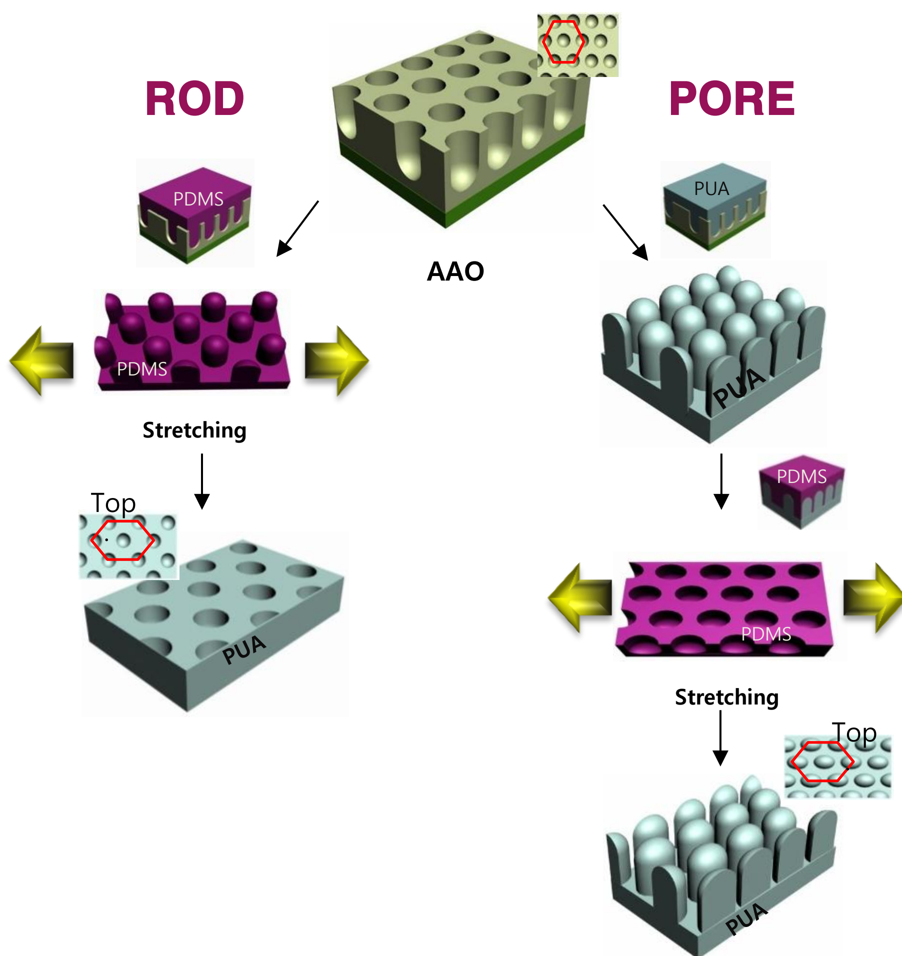


Figure 4. Whole process for fabrication of stretched patterns.

3 Results and Discussion

3.1 Sub-100 nm scale PDMS molds

3.1.1 Anodic aluminum oxide

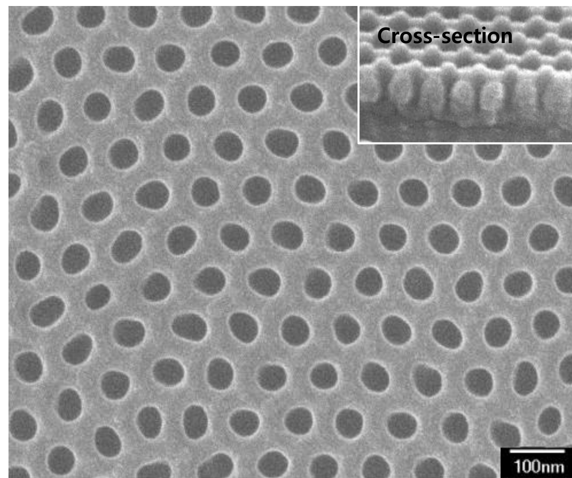
Master mold is obtained from self-assembled anodic aluminum oxide (AAO) that is hexagonal arrangement of pores. Pore diameter of the AAO is about 60nm and these are well-ordered hexagonally packed in Figure 5 surface and a cross-sections of the AAO images. Distance between centers of pores is designated by applied electric field and other specs such as pore length and diameter are controlled by reaction time. Especially, its diameter is adjusted with wet etching (in acid solution) after the anodization.

3.1.2 Sub-100 nm patterned PDMS molds

From AAO (pore, master mold), replication is repeated several steps according to its purpose. Before replication, all the master molds except for PDMS molds are modified hydrophobic for easy remolding. First replicas from AAO are rod structures with PUA and PDMS in Figure 6 that are differently made regarding to properties of materials. Because PUA is rigid and flexible chemical, replication process is easy and cured PUA molds are strong enough to endure electron beam (SEM). On the other hand, due to weak

property of PDMS, these are only measured by Atomic Force Microscope (AFM). The rod patterns have the same structure but their usage is different. rod PUA is middle step for fabrication of pore structured flexible PDMS molds. Rod structured PDMS molds are directly fabricated from the AAO without the middle step. The pore structured PDMS is confirmed by which is replicated from PUA rod pattern. Investigations about the fabrication of small pattern (sub-100 nm) have been researched with various composite materials represented by PUA(MINS, MINUTA TECH). However, these are rigid to prevent deforming the pattern and make high-resolution patterns. In this study, several methods were conducted to utilize perfect replicating property of previous composite materials at stretching but those were all failed. PDMS was the most appropriate source for the replication of patterns and elastomer PDMS was the best for stretching. Very small sized pattern which is fewer than one hundred nanometer had been difficult to transfer only with PDMS(Figure 6 toluene free patterns) because of its poor wettability to the master pattern structures. This had been overcome by Namil Koo[18] simply diluting PDMS with toluene. Unfortunately, patterns made with diluting PDMS were only shown by AFM because the small pattern scale needs appropriate electron beam current but PDMS is easily degraded by electron beam (SEM) leading to difficulty to see original

morphology. These AFM images are at Figure 6 which present even pattern structures as uniform color AFM images. These small scale patterns are uniformly formed 2cm x 1cm overall area. The more ratio toluene to PDMS, the clearer images are got. A PUA stamp is used repeatedly (over 10 times) when fabrication of PDMS molds. This is confirmed by AFM images showing the same pattern images (Figure 7).



center-to-center	110 nm
Pore diameter	60 nm
Pore depth	100 nm

Figure 5. SEM images of anodized aluminum oxide with a surface of AAO and a cross−section in inset that has 41 nm sized diameter and 100 nm depth.

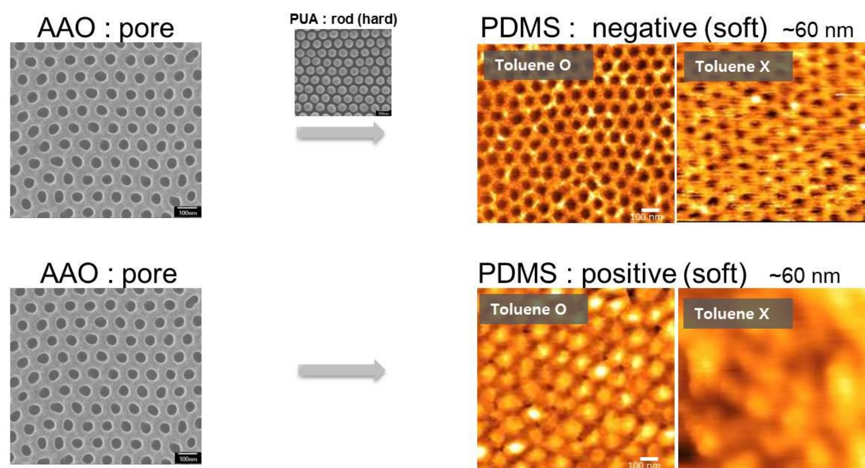


Figure 6. High resolution of PDMS molds (positive and negative patterns).

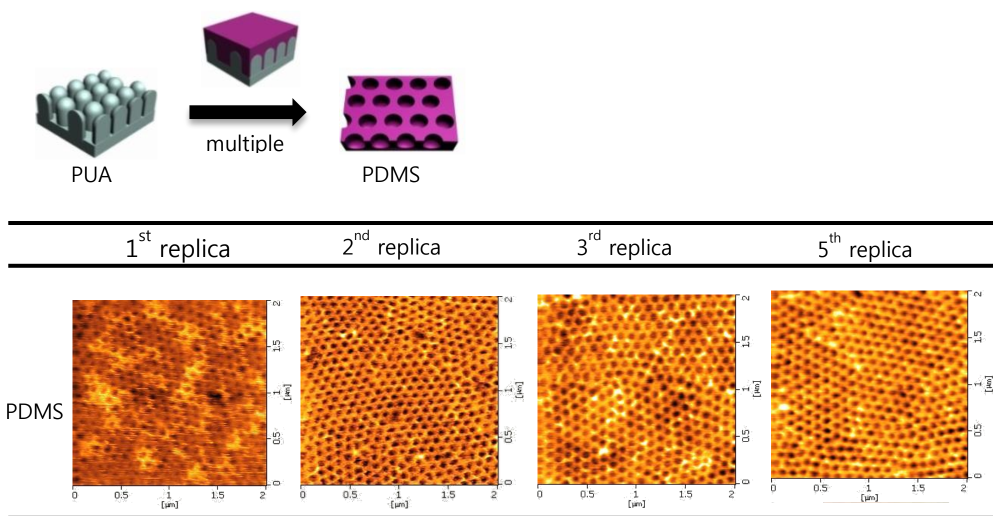


Figure 7. Schematic image of pattern transferring from the PUA to PDMS and topological AFM image of several PDMS molds using the same PUA stamp.

3.2 Shape and arrangement control

After making PDMS molds, force is applied to the flexible molds by stretching tools and adjusted strain gives different arrangements and shapes of features (rods or pores of each pattern). The elongation of pore pattern gives rise to varying its shape as well as the pore arrangement. Results from gradual increase of the strain from 0% to 80% are showed in Figure 8 for PUA rod structures replicated from the stretched pore PDMS.

The arrangement change is identified by Fast Fourier Transform (FFT) of each images placed in Figure 8 that a circle line means regular hexagonal array but ellipse is for elongated hexagonal packing. As the force gets strong, the FFTs get sharp ellipses and these varied conformations are certainly confirmed at Figure 8. For more accurate analysis, profiles of each FFT are plotted at Figure 9. As colors of the rings are brighter, profile heights rise. In stretching direction, gaps between secondly highest peaks become narrow as increasing the strain meaning arrangement in this direction elongated. On the other hand, perpendicular to the stretching direction shows the same gaps between those.

3.2.1 Shape analysis

At the same time, the shapes of features change from the circle to the ellipsoid that each long axis diameter is 75, 92, 102, 111, 116

nm for each 0, 0.2, 0.5, and 0.8 stain. These size specs are plotted at Figure 10 and shows that diameters in long axis (stretching direction), D_L, increase and diameters in short axis, D_S, decrease as raising the strain. Slope (variation of the length) of D_L is bigger than that of D_S because of Poissons effect (When a PDMS is stretched in one direction(x aixs), it usually tends to compress in the other two directions(y, z axis) perpendicular to the direction of stretching). The increased diameter doesn' t agree with its strain. For example 1.8 times of 75 nm is 135 nm but the D_L of strain 0.8 is 116 nm. Nevertheless the size of patterns is apparently controlled by the applied load. The shape of this elongated pattern is characterized as D_L to D_S ratio, aspect ratio (AR). These values are 1, 1.24, 1.53, 1.56, and 1.85 for strain 0, 0.2, 0.4, 0.5, and 0.8 respectively. These are also plotted comparing with theoretical values. When the strain(ε) is applied to the PDMS molds, diameter in long axis becomes $D_L=(1+\varepsilon)D_0$ and in the other direction becomes $D_S=(1-0.5\varepsilon)D_0$. 0.5 is Poisson' s ratio for the elastomer PDMS and D_0 is diameter of un-treated pattern. Finally aspect ratio is

$$\mathrm{AR} = \frac{D_L}{D_S} = \frac{1+\varepsilon}{1-0.5\varepsilon}$$

In this plot, experimental values are similar with theory at initial point but large deviation is observed in the end. Observed D_S have

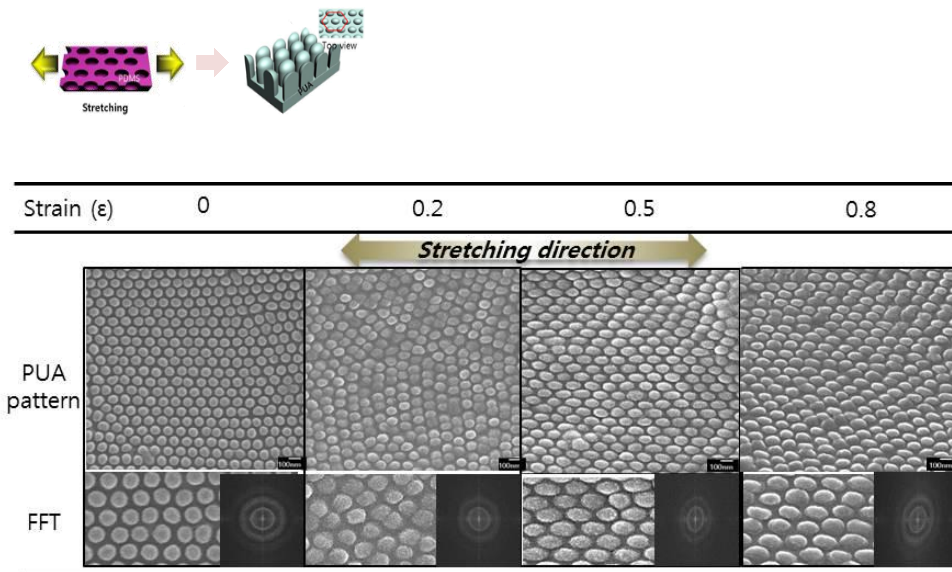


Figure 8 Images of replications of shape control by stretching flexible pore structured molds. From left to right, strain increases 0 to 0.8 and pattern shapes change circle to ellipsoid. Rings in small boxes are Fast Fourier Transform of each images meaning anisotropic arrangement.

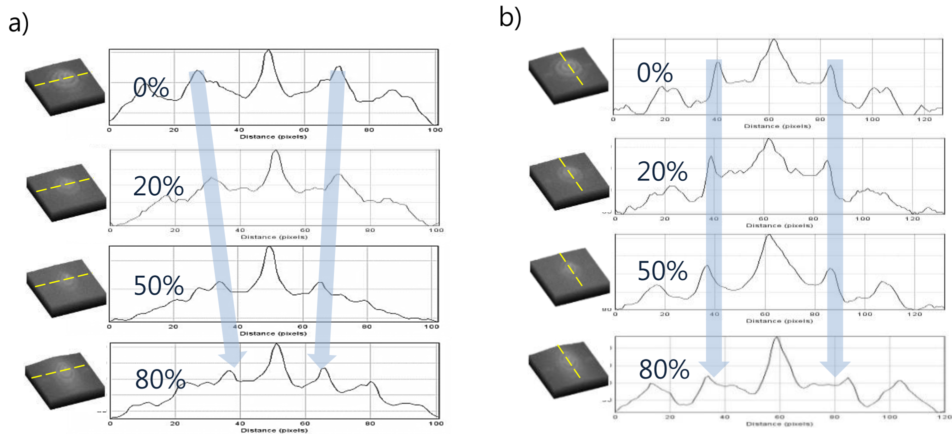
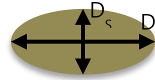


Figure 9. Profile plots of pore elongated pattern FFT (a) in short axis show decreasing gap between second peaks and center peak as strain increase and (b) in long axis show equal gap.

a)



Strain (ε)	0	0.2	0.4	0.5	0.8
D_L (nm)	75	92	102.5	111	116
D_S (nm)	75	74	66	71	63

b)

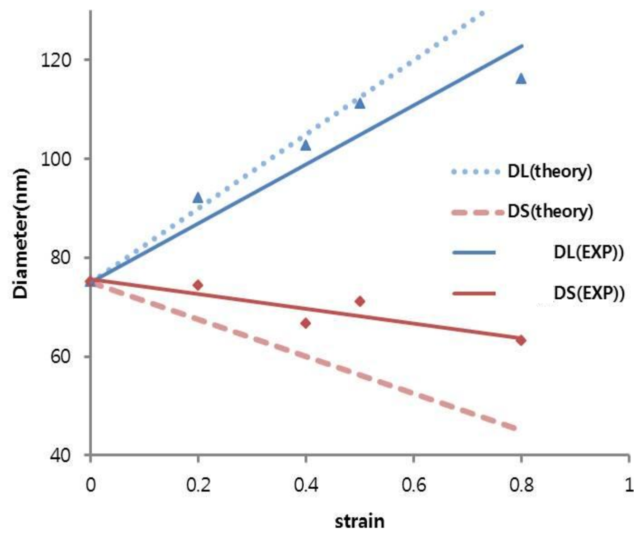
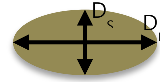


Figure 10. a) Table of diameter at long axis and diameter at short axis. b) Plot of pattern features size, long axis diameter D_L and short axis diameter D_S.

a)



Strain (ε)	0	0.2	0.4	0.5	0.8
Aspect ratio	1	1.24	1.53	1.56	1.85

b)

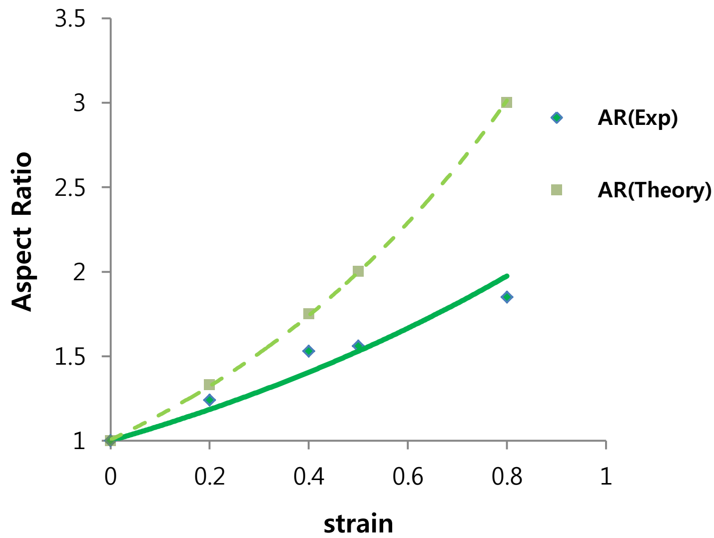


Figure 11. a) Table of aspect ratio for each strain b) plot of aspect ratio.

big deviations from the theoretical calculation and this leads the aspect ratio difference. When high strain is applied to the sample, this elastomer strongly tries to recover its original state and slightly goes back to opposite site. This event happens at UV curing and is difficult to distinguish how much recovered. Therefore high strain would be inaccurate.

3.2.2 Anisotropic wetting behavior

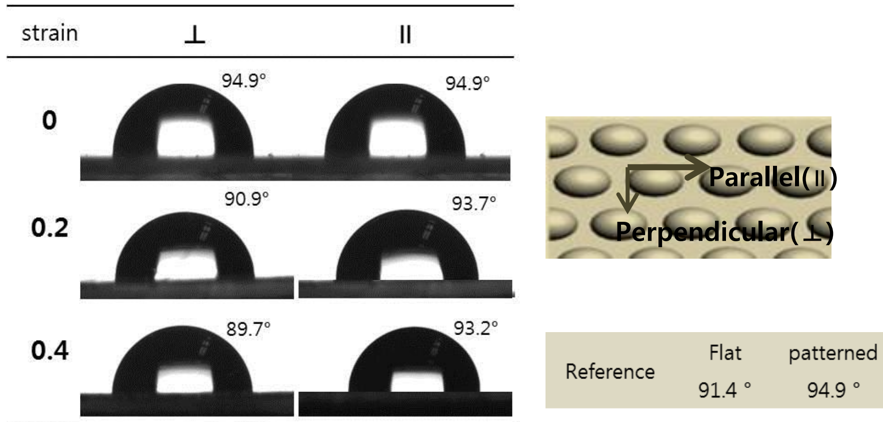
Elliptical morphology has unique optical and wetting properties. Especially wettability is directional due to anisotropic patterns. Contact angle of water drop is measured on the 20% and 40% stretched rod structure surface at different directions (Figure 12). Side view on the stretching direction is parallel angle and rotated 90° from parallel side view is perpendicular. Static contact angle is larger for parallel direction than perpendicular. Contact angle at parallel direction is 90.9° and 89.7° for stain 0.2 and 0.4 and opposite direction angles are 93.7° and 93.2° for strain 0.2 and 0.4 respectively. Differences between parallel and perpendicular angle increase as the strain increase. This result agrees with thermodynamically explained theory. Reference 1 uses three-phase contact line (TPCL Figure 13) to calculate surface free energy as a function of instantaneous contact angle. TPCL is a line meeting solid (pattern), liquid (water drop) and gas (vapor).

Anisotropic wetting is caused by different energy barrier that overcome the moving of TPCL along the perpendicular direction to the fixed axis[1]. Also, degree of anisotropic wetting is increase as period decrease. In this study in case of parallel direction (long axis) energy barrier that overcome TPCL moving along the perpendicular direction (short axis) is larger than energy barrier of perpendicular (short axis) that overcome when TPCL moves along parallel direction (long axis). Because the period of parallel (long axis) is larger than that of perpendicular (short axis), TPCL moving along the parallel has lower barrier energy. Therefore, contact angle at parallel direction is larger than contact angle at perpendicular. This anisotropic wetting behavior is induced from 100 nm scale elongated dot patterns. This anisotropic wetting morphology could be applicant for tunable/switchable surface and biosensors[22].

3.2.3 Strain difference in a PDMS mold

Difference of strain in a stretched PDMS molds is present in Figure 13 with AFM images. Because the edge area receives bigger strain than the center, the feature size at edge area is larger than that at center part. Depths of each feature were measure deeply at the edge part but difference is below ten nanometers. This problem is resolved by using only center part for this study and relatively small (1 cm X 1.5 cm) PMDS molds (figure 14).

Stretched PDMS state could not be confirmed with image for about 100 nm scaled above samples. When pattern size gets bigger over 300 nm, stretched pattern could be shown by SEM with relatively thickly coated Pt and low beam current. This is Figure 15 that the elongated pore is clearly ellipsoids but the rod is not. However, FFT in insets show elongated rings meaning varied arrangement.



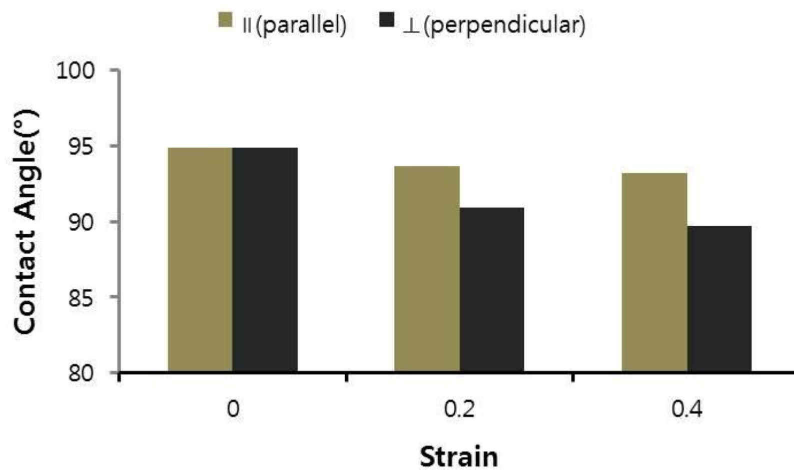


Figure 12. a) comparison of contact angles between parallel and perpendicular at each strain 0, 0.2 and 0.4, b) Side views of a water drop on the surface with the perpendicular and parallel directions for strain 0, 0.2 and 0.4 respectively.

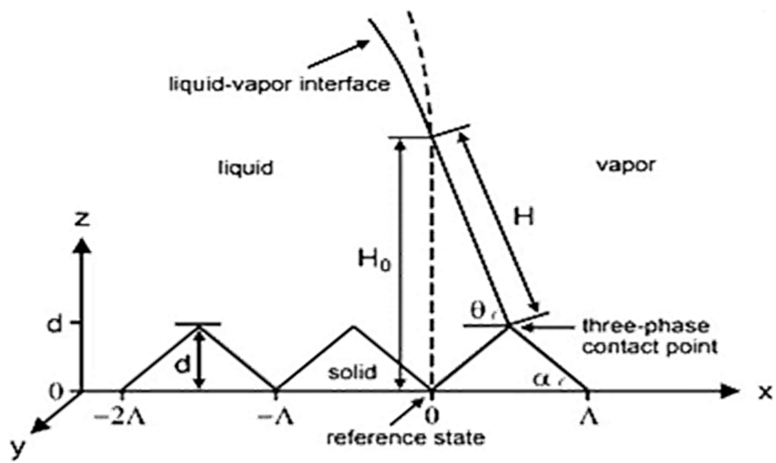
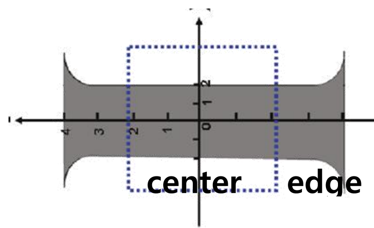


Figure 13. Three-phase contact line (TPCL) [1].



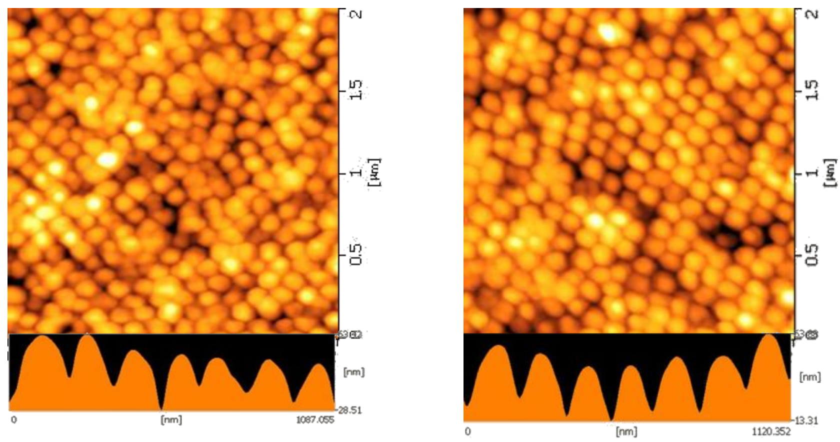


Figure 14. Strain difference in a stretched PDMS molds.

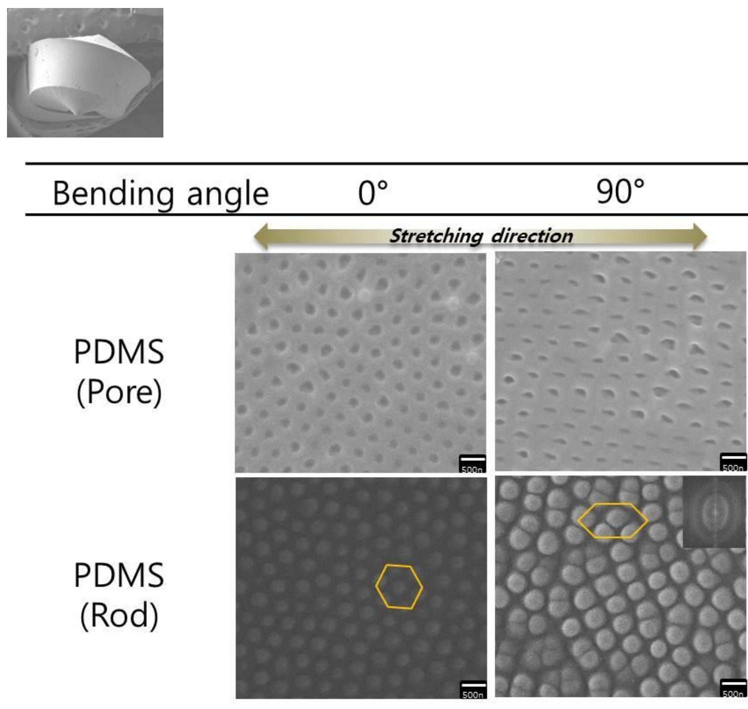


Figure 15. SEM image of stretched PDMS molds having ~220 nm diameter pore and rod structure. These are taken in bended state at 90° and smaller than 90° (in situ).

3.3 Arrangement control

When the rod patterned PDMS receives uniaxial force, the arrangement of the rods is changed but circle of this does not change because the upper part of standing rod does not receive force at stretching. Replications of the 20% and 50% stretched rod structure are showed in Figure 16 with their FFTs. Un-stretched sample is similar with the image of AAO. The arrangement change is difficult to recognize at the images but the below FFT shows that circle is transformed into ellipsoid which is anisotropic array. To clear result of FFT, profile of FFT is plotted in Figure 17. Like the preceding, profile of long axis shows decrease in gaps between secondly highest peaks. Diameter of pore pattern is similar between stretched pattern images. Anisotropic order of pattern is hardly formed from self-assembly but this is very simple and economically beneficial method. Even though the stretching has been used deforming the pattern shapes, the arrangement change with the same pattern shapes has not been reported before.

Hexagonal array has two kinds of stretching direction that one is three dots in triangle (∴) and the other one is two dots in line (:). If the triangle is stretched, square pattern and elongated hexagonal array are formed. On the other hand, by expanding two dots line stretched ellipsoid and array are present[11]. Because the AAO has

many grains that one grain has one orientation, the stretching direction cannot be controlled. Also the transformed pattern shape is identical in this study due to small elongated magnitude because different characters are observed over 100% strain.

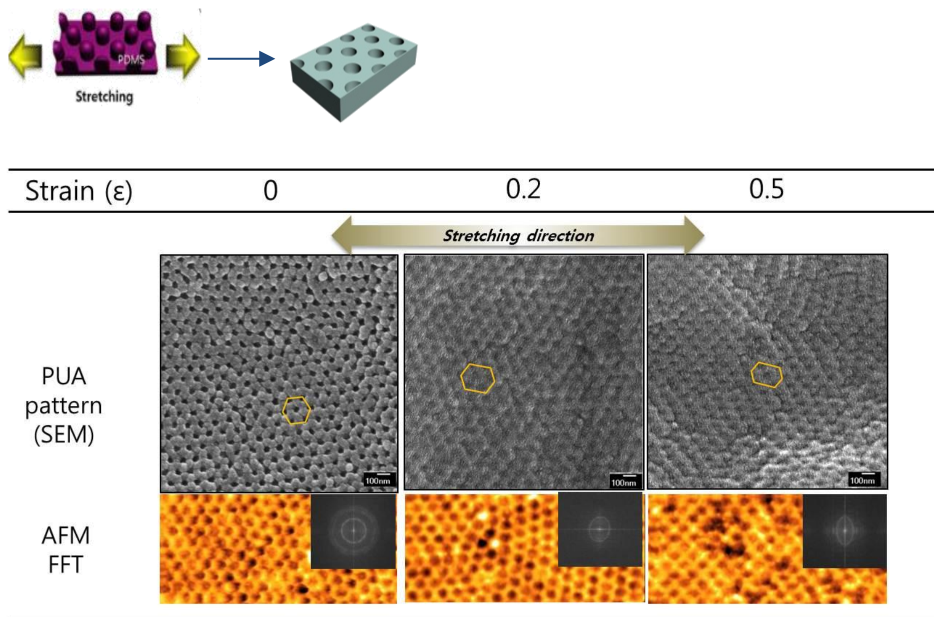


Figure 16. Images of replications of arrangement control by stretching flexible rod structured molds. Pore arrangement is originally hexagonal but 20, 40% strained images are elliptical hexagonal arrangements.

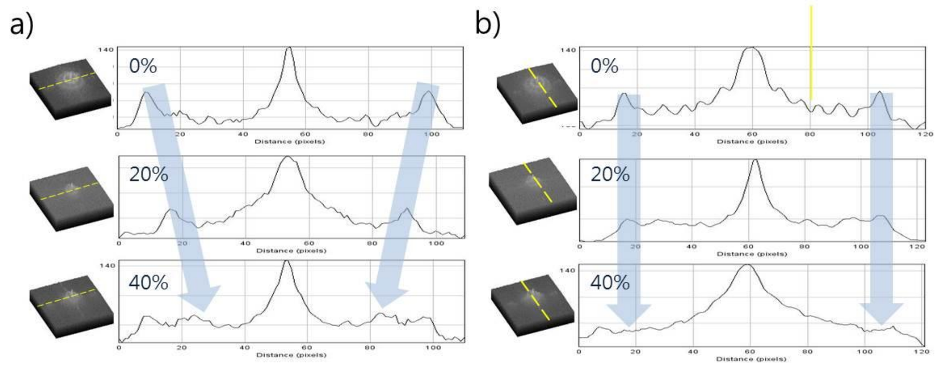


Figure 17. Profile plots of pore elongated pattern FFT (a) in short axis show decreasing gap between second peaks and center peak as strain increase and (b) in long axis show equal gap.

4 Conclusion

Nano dot patterns with elliptical shape and anisotropic arrangement were formed by stretching pore structured flexible master molds as controlling its shape with the applied loads. Also, asymmetric array hole patterns were fabricated by elongation of rod molds. The master mold, self-assembled AAO has advantages in terms of costs, time efficiency, and various size patterns as the master molds compared with conventional photolithography methods. High-resolution sub-100 nm scale patterns of PDMS are fabricated with diluting PDMS method. Different shapes and arrangement were obtained from one master mold using stretching method that is easily controllable. The size of pattern reached from 75 nm to 116 nm and degree of asymmetry, aspect ratio, was attained as 1.85 and compared with theoretical values. Especially, while the shapes of feature are remained, only the arrangements changes were induced by the rod elongation. Asymmetric arrangement with dot patterns is also new nano molds. These elliptical patterns have anisotropic wetting property that long axis contact angle is larger than that of short axis coming from different energy barrier of two direction. This anisotropic wettability is induced from 100 nm scale asymmetric dot patterns. Stretched state of high-resolution pattern could not be observed due to weak

property of PDMS but elongated the bigger sized PDMS pattern could image. Stretching flexible molds is facile and environmentally friendly method as it is based on physical process. The applied load to the elastomer PDMS molds is a factor to control of pattern shapes and arrangements. When manipulating the anisotropic morphology, this study can be utilized very simply.

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국문초록

포토 리소그래피의 시간적, 경제적 문제로 인해 다양한 소프트 리소그래피가 개발되었고 여전히 여러 분야에 적용될 리소그래피 방법들이 연구되고 있다. 여기에서는 경화성 고분자를 이용한 복제 몰딩(replica molding, REM)으로 나노 스케일의 비등방성 패턴 형성에 주목하였다. 하나의 수십 나노 크기를 갖는 정육방정계의 도트 패턴(dot pattern)에서 새로운 모양과 배열을 갖는 스탬프를 제작하여 활용하고자 한다. 패턴의 마스터 몰드는 자기 조립으로 쉽게 얻을 수 있는 양극 산화 알루미늄(Anodic Aluminum Oxide, AAO)을 이용하였고 여기서 얻어지는 패턴의 모양은 원통형의 기공이고 배열은 육방정계이다. 모든 패턴의 표면은 소수성으로 개질시켜 여러 번 전사가 가능하게 하여 하나의 몰드에서도 다양한 패턴이 나올 수 있어 매우 경제적인 방법이다. 패턴 전사는 소프트 리소그라피에서 주로 사용되는 PDMS(poly(dimethyl siloxane))을 사용하였는데 PDMS로 수십 나노 크기의 패턴의 복제는 어려웠으나 젖음성를 조절하여, 50nm의 양각 패턴과 음각 패턴을 모두 얻는데 성공했다. PDMS를 사용한 가장 큰 이유는 이것의 고무 같은 성질 때문에 패턴을 망가뜨리지 않으면서 변형을 줄 수 있다는 점 때문이다. 이 점으로 패턴의 모양을 원에서 타원형으로 변형시켰고, 패턴 모양의 종횡비(aspect ratio)도 조절할 수 있다. 또한 패턴의 모양은 유지하면서 배열만 바꿔주어 동일한 모양의 패턴을 원할 때 적용시킬 수 있도록 하였다.

마지막으로 이러한 비등방적 구조의 패턴이 갖는 방향성이 있는 젖음성을 측정하여 활용가능성을 확인하였다.