Creating ordered microwells that have controlled curvatures is an important aspect in the areas of microfabrication, nanotechnology, and materials science.1–3 Most of the available methods of fabricating such curved microstructures are based on reducing surface energies or controlling reactant/product diffusion.4 Surface energy minimization drives the formation diameter- and shape-controlled micro/nanoparticles.5–7 Particles with various aspect ratios or shapes have been prepared by blocking certain facets of growing particles.8–10 Hemispherical microdomes of polymeric materials have been generated by melting polymer films supported on solid substrates, where the trend of reducing the surface free energy determines the curvature of the final structure.11 Patterned microdomains with alternating hydrophilic and hydrophobic regions can confine liquid droplets,12 which have a surface energy between those of hydrophilic and hydrophobic areas. The droplets could then be solidified through a thermal- or light-induced polymerization process to make solid structures of the same shape. Curved microwells have been made at the end of an optical fiber or by imprinting microspheres on polymer films.13–16 Heterojunction nanowires that have both hydrophobic and hydrophilic sections could self-assemble into curved mesoscopic structures to reduce the surface energy.17

Wet chemical etching is a process that utilizes a liquid chemical to remove materials from substrates to make small structures. Depending on the rate of reaction, the etching can be diffusion-controlled or reaction-controlled, which will produce etching cavities with different profiles. When the etching is controlled by surface reaction kinetics, the shape of the resulting cavity could be predicted by geometric considerations, provided the etching rate is known for different materials or crystallographic orientations. If the chemical etching is controlled by the mass transfer to or from the etching surface (i.e., the surface reaction is very fast), the shapes of the resulting structures will depend on the local fluid velocity profiles as well as on the concentration distribution of reagents and/or products. The deformation of the cavity during the etching process affects the local fluid flow and the etchant concentration distributions, which in turn affects the shape evolution of the etched structures.18 In addition, most chemical etching processes need to use an inert mask to protect the solid surface selectively to produce patterns in the etching process. The mask could lead to a characteristic undercut that makes the prediction of the etching profile difficult.19 Wet etching of a sample with homogeneous composition without using masks will produce randomly distributed dimples with various curvatures because of the uncontrolled distribution and size of defects.

Instead of using masks to produce curved micro/nanostructures, we have established a method to fabricate arrays of curved microstructures (i.e., microwell) by the diffusion-limited wet chemical etching of ordered composites composed of two different types of glass materials. In this method, fiber-drawing nanomanufacturing (FDN) is used to produce the glass composites with well-defined size, location, and arrangement of each component. A chemical etchant that will preferentially attack one component of the glass composite will produce an ordered array of microwells (Figure 1). The ordered composites and the wet etching could be considered to be undeveloped films and the developing process to generate pattern. By engineering structures of glass composites, the position and spacing as well as the dimensions of etched structures are controlled with high precision. The keys to the success of this method are (1) the creation of bulk glass composites that have ordered microfeatures, (2) the...
identification of an etchant that shows large contrast in the etching rates for two glasses, and (3) the diffusion-limited wet etching of glass composites. The structures of etched microstructures are determined by fiber drawing and wet etching. The spacing and the diameter of the structures are determined by the sizes of starting glasses and drawing and etching conditions. Previously, the fiber-drawing method has been used to fabricate glass nanochannel and nanocone arrays and vertically aligned alloy and semiconductor micro/nanowires. This work extends the application of fiber drawing to the high-yield controlled production of curved microwells, which could be used as an enabling tool for high-throughput synthesis, analysis, and screening of materials and biomolecules. This method is intended to be complementary rather than replace photolithography techniques that have much better structural controls in making large samples at low cost. Compared to photolithography, this method provides a new mechanism by which we could intentionally control the surface reactivity of a solid material at certain locations. Further extension of this method to other materials systems such as polymer or metal would be quite different from the existing photolithography techniques. From a more material perspective, the method provides a possible way to achieve large arrayed microstructures on glass surfaces, but photolithography usually works on silicon or other semiconductor substrates.

We have selected two types of glasses as starting materials, one in the form of a rod and another in the form of a tube. The diameter of the rod is slightly smaller than the inner diameter of the tube. These two types of glass materials have similar thermophysical properties (i.e., softening temperatures and coefficients of thermal expansion) but very dissimilar chemical resistance to an acidic etchant. The glass rod contains more borate coefficients of thermal expansion) but very dissimilar chemical resistance to a glass tube with a 7.5 mm inner diameter and 12.5 mm outer diameter and high chemical resistance. This preform is then drawn into a long fiber with an average diameter of 400 µm at 880 °C and cut into short pieces of equal length (600 mm). During fiber drawing, the tube is evacuated using a pump to ensure intimate contact of the tube and the rod. These short glass pieces are then stacked together to form a bundle, followed by the next fiber-drawing cycle. By repeating the draw-cut-stack process several times, the diameter of the glass rod and the wall thickness of the glass tube will decrease from millimeters to submicrometers. After the last drawing cycle, the stacked fiber bundles are annealed at 760 °C to form a glass rod, which is cut into 2-mm-thick plates using a low-speed diamond saw and polished with diamond polishing films, which have grain sizes of 3 and 1 µm, respectively.

Glass etching is carried out at 20 °C in a mixed solution containing hydrofluoric acid (HF) and buffered oxide etchant (BOE). A series of etching solutions have been prepared that include 4% (by volume) HF and 0, 2.5, 5, or 10% BOE. Wet etching is carried out in a quiescent solution in order to reduce convective flow, allowing the diffusion of molecules to be dominant. The BOE maintains a nearly constant etching rate by keeping the concentration of fluorine ions constant. The etching time is varied from 5 to 90 min. After the chemical etching, the samples are rinsed with deionized water, dried in a nitrogen flow, coated with a thin film of platinum, and imaged using a JEOL 6400 field-emission scanning electron microscope (SEM). SEM images show ordered microwell structures over a large surface area (1 cm²) on most samples (Figure 2A), where all images are collected at a 30° sample tilt angle. The images along the x axis (from left to right) correspond to etching times of 5, 30, 60, and 90 min. The images along the y axis (from top to bottom) correspond to BOE concentrations of 0, 2.5, 5, and 10%. To measure the structural parameters of each sample, the microwell structures are used as templates to form a polydimethylsiloxane (PDMS) replica, and the thus-produced microdromes on PDMS films are imaged by SEM. Briefly, a 10:1 mixture of PDMS prepolymer and curing agent (by weight) is poured onto a microwell array. The thickness of the PDMS layer is about 1 mm. After curing in an oven at 70 °C for 15 min, the PDMS film is removed using a sharp scalpel. Figure 2B shows SEM images of the PDMS microdromes after depositing thin films of platinum to avoid charging effects, where each image corresponds to an image in Figure 2A at the same position. The curvature of each microwell has been derived from the image by drawing a cross-sectional line along the center of a polymer micromodule. Figure 3 shows the well depths as functions of etchant concentration and etching time. Figure 3A shows the BOE-concentration-dependent height change of the structures, where halves of curves are shown. As the BOE concentration increases, the height of the well will decrease (from top to bottom). This is because higher BOE concentrations will have less chemical contrast with respect to the etching of two glasses. Figure 3B shows the time-dependent height change of the structures, where halves of curves are shown. As the BOE concentration increases, the height of the well will decrease (from top to bottom). This is because higher BOE concentrations will have less chemical contrast with respect to the etching of two glasses. Figure 3B shows the time-dependent height change of the structures, where halves of curves are shown. As the BOE concentration increases, the height of the well will decrease (from top to bottom). This is because higher BOE concentrations will have less chemical contrast with respect to the etching of two glasses.

References:
The diameter and spacing of a microwell are determined by the geometries of the starting glass tube and glass rod as well as the drawing conditions. For a given preform, the size and spacing reductions are achieved by repeating the simple draw–cut–stack process. Because the total mass of the preform is conserved during fiber drawing, when the length of the fiber increases, both the diameter of the core glass wires and the spacing between two adjacent glass wires will decrease. To understand the deformation of the glass tube and glass rod in the size-reduction process, we have measured the diameters and spacing of wells and the outer diameters of the surrounding glass. Because the glass fibers obtained after a certain number of drawing cycles offer only a limited amount of information, the short tapered pieces that are left after each drawing cycle are used to provide more data on the deformation. Basically, the tapered pieces with a continuous change of diameter from several centimeters to hundreds of micrometers are sliced into thin plates of different outer diameters. Each slide is polished and etched to expose the diameter of the microwell. The diameter of each sample is measured as a function of the diameters of surrounding glass.

For the first drawn fibers, the diameter of the surrounding glass equals that of the fiber diameter. For the second drawn fibers, the diameter of the surrounding glass is defined as the sum of the diameter and the spacing of the wire. The samples are etched under the same conditions (time and concentration). Figure 3C demonstrates that as the diameter of the surrounding glass decreases from 326 to 135 µm the diameter (triangle) and the spacing (diamond) of the glass rods decrease linearly, suggesting that the diameter and the rod spacing are dependent on the diameter of the surrounding glass. In addition, the two lines have different slopes, originating from the different coefficients of thermal expansion of the two glasses. The ratio of the coefficients of thermal expansion of two glasses is derived as 0.86 from these curves. Such a ratio does not change when the size of the surrounding glass decreases linearly to 135 µm.

From another aspect, we have derived the relation between the diameter (and spacing) of inner glass and the fiber-draw cycles by taking into account the contributions from the ratio of coefficients of thermal expansion. The wire diameters after the first, second, and third draw cycles could be derived using the following equation:

\[ d_n = \frac{(\Phi_1)^n R}{(2 + t)^{n-1}(R + T)} \]

where \( d_n \) is the diameter of wires after \( n \) time’s draws, \( \Phi_1 \) is the outer diameter of fiber after \( n \) draws, \( R \) is the inner radius of the glass tube in the first draw cycle, \( r \) is the inner radius of the tube in the second and third draw cycles, \( T \) is the thickness of the glass tube in the first draw, and \( t \) is the thickness of the glass tube used to encircle the fiber bundles that are obtained in the second and the third draws. The interwire spacing during the fiber-drawing process could be derived from the following equation

\[ l_n = \frac{(\Phi_1)^n \eta^n T}{(2 + t)^{n-1}(R + T)} \]

where \( l_n \) is the spacing between two wires after \( n \) time’s draws. \( \beta_1 \) and \( \beta_r \) are the coefficients of thermal expansion of the glass tube material and the glass rod material at the drawing temperature, \( \eta \) is the ratio of \( \beta_1 \) and \( \beta_r \). \( \Phi_1, R, T, r, \) and \( t \) have the same meaning as those in eq 1. Using the dimensions of the glass tube, glass rod, and outer diameter of the fiber bundles, we have calculated the diameter and spacing after the first and the second drawing cycles. Furthermore, the actual diameter and spacing after the first and the second drawing cycles are measured from SEM images. Both sets of data are indicated in Table 1. The calculated and measured values of the diameter and spacing for the first draw cycle differ from each other by less than 5%, but the values for the second draw cycle are larger than 10%, which could be induced by cross-interface diffusion of glass materials in the fiber drawing and annealing processes. The spacing of the second draw fibers is shorter than the calculated value because the etchant will also remove the shell glass, though to a relatively small extent.

The ordered arrays of curved microstructures imprinted on PDMS films have shown unique optical properties. The PDMS microdomes could focus and diffract incoming light and generate diffraction patterns. The optical micrographs of microdomes are collected using an Olympus optical microscope (BX51M). The PDMS films are fixed onto the sample stage of the microscope and illuminated from the back by parallel light. The microdomes

\(_{(31)} \text{Yang, S.; Aizenberg, J. Nanotoday 2005, December, 40.} \)
Figure 3. (A) BOE concentration-dependent curvature changes, the curves from top to bottom correspond to BOE concentration of 0, 2.5, 5, and 10%. (B) Time-dependent curvature change, the curves along the x axis (from left to right) correspond to etching time of 5, 30, 60 and 90 min. (C) Diameter and spacing reductions as functions of the diameter of the surrounding glasses, the diamond and triangle lines correspond to the spacing and diameter.

**Table 1. Diameter and Spacing of Glass Structures after the First and Second Drawings**

<table>
<thead>
<tr>
<th></th>
<th>$D_{cal}$ (μm)</th>
<th>$D_{exp}$ (μm)</th>
<th>$(D_{cal} - D_{exp})/D_{exp}$</th>
<th>$S_{cal}$ (μm)</th>
<th>$S_{exp}$ (μm)</th>
<th>$(S_{cal} - S_{exp})/S_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st draw</td>
<td>239</td>
<td>234</td>
<td>+0.21%</td>
<td>266</td>
<td>255</td>
<td>+4.3%</td>
</tr>
<tr>
<td>2nd draw</td>
<td>3.3</td>
<td>3.9</td>
<td>−15.4%</td>
<td>2.78</td>
<td>2.38*</td>
<td>+16.7%*</td>
</tr>
</tbody>
</table>

focus the parallel light to form bright spots, which are observed through the objective of the microscope. Figure 4A shows the optical images of PDMS microdomes that are brighter than the background. We have measured the intensities of light focused by microdomes to reflect the curvatures of microwells. The digitalized brightness of one bright spot has been measured on each sample using normalized brightness of the dark area as a standard (Figure 4B). Figure 4C shows the diffraction pattern of a typical PDMS sample with microdomes illuminated by a He–Ne laser beam (670 nm). The distance between the laser source and the PDMS film and the distance between the PDMS film and the screen are 4.1 and 223 cm, respectively. The characteristic hexagonal pattern also confirms the ordered arrangement of microdomes on the PDMS film.

We have used a Monte Carlo method to model the differential wet etching of a smooth cross section of a glass plate. The glass plate consists of a bundle of parallel glass fibers that are arranged in a hexagonal pattern and embedded in another type of glass. The two glasses have different etching rates when exposed to solution. A periodic boundary condition is applied in the simulation. The repeat unit is divided into an array of 1000 columns × 866 columns of the same height. The edge length of the column is determined by the dimensions of the repeat unit. The etching process is then modeled by spreading $10^6$ etchant droplets on the surface randomly. The radius of the droplet is 10 cm, which will not affect the final results when the radius is slightly changed. Only those columns covered under the droplet will be etched in each step. The etching is controlled by the diffusion rate and the chemical reaction rate of the solution with different types of glass. The etching rate for each column is described by a simple mode shown in eq 3

$$r_{etch} = \begin{cases} (h - h_0)R_{diff} + r_{chem} & h > h_0 \\ r_{chem} & h \leq h_0 \end{cases}$$

where $r_{etch}$ is the etching rate, $h_0$ represents the height of the glass column at the center of the water droplet, $h$ denotes the height of the columns covered by the etchant droplet, $R_{diff}$ and $r_{chem}$ refer to the diffusion- and chemical-reaction-rate-controlled etching rates, respectively. From eq 3, we may learn that when the etching is controlled by the diffusion rate a relatively flat surface will be obtained because the etching rate is proportional to the height of the column. When the etching is dominant by the chemical reaction rate, microwells with sharp edges will be obtained depending on the relative chemical reaction rates of the glasses with the etchant. When both the diffusion and the chemical reaction rate play roles in the etching process of the glass, rounded microwells are obtained as shown in the experiments. Figure 5 shows an example of the simulation results, where the surface is modeled by a 10.8 × 9.35 μm² grid. The core glass is represented by 0.87-μm-radius cylinders that are arranged in a hexagonal array with a center-to-center distance of 5.4 μm. $r_{chem}$ is 27 nm per droplet for the core glass and 22 nm per droplet for the shell glass. $R_{diff}$ for both glasses is 10% of the corresponding $r_{chem}$.

The glass microwells could be used for protein crystallization, where many samples with different crystallization conditions can be tested simultaneously using small amount of sample. On the basis of SEM images, the volumes of microwells created in this method could be controlled to be as small as 30 fl. We have used microwells to make microcrystals of sodium chloride


and a protein. A droplet of solution that contains the desired materials at a suitable concentration is dropped onto the surface of a microwell array. The evaporation rate of solvent is controlled to achieve slow, uniform evaporation over the whole surface area (Figure 6A). Figure 6B shows the SEM images of the microcrystals of sodium chloride (salt) formed inside microwells. The sizes of the salt microcrystals depend on their concentrations in the initial solution. As the concentration decreases, the size decreases. Nanoparticles of uniform diameter are achieved by decreasing the salt concentration from 1 to 0.05%. Assuming the original solution covers the whole surface area of the microwell array and no redistribution of salt occurs in the evaporation process as a result of its existence on each glass microwell, the initial concentration of salt can be estimated from the volume of each nanoparticle to validate the experiment. The estimated concentration (0.048%) of the salt is close to the original one (0.05%), which suggests that the method has good control over the amount of liquid dispensed into each microwell. In the case of protein crystallization, an evaporation chamber is utilized to control the rate of water evaporation. Figure 6C is an optical image of microcrystals of a protein, bovine serum albumin (BSA). The sizes of the protein microcrystals are uniform when the concentration of proteins in the initial solution is in the range of 0.05 to 0.1%. The underlying glass structures could be identified in Figure 6D. By using fluorescence-labeled BSA, we have used fluorescence microscopy to confirm the crystallization of the protein (Figure 6E). The attached protein microcrystals are aligned in an ordered array. Compared to flat-bottomed microwells, curved microwells could help to dispense liquid in each microwell. As the liquid–solid contact line passes each microwell, the protein concentration becomes larger. Eventually, all solvable species are accumulated in the lowest part of the curved microwell. In contrast, in the case of a flat-bottomed microwell, the liquid covers the whole flat bottom. In addition, the open access of curved microwells makes the further manipulation and characterization of protein microcrystals much easier compared to those of straight columnar microwells.

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