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Original Article

CONSTRUCTION OF THREE-DIMENSIONAL MICROSTUCTURES TO BE USED IN STUDIES OF THE CUTANEOUS PERCEPTION OF TEXTURE

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Abstract—*Photolithography procedures are described which allow three-dimensional microstructures to be constructed for use in studies of the cutaneous perception of surface texture. A computer-generated two-dimensional drawing of the desired pattern is photographed and the film negative used as a mask to pattern photoresist-coated glass or oxidized silicon. The photoresist not exposed to light serves as a mask when the glass or silicon is placed in an etchant. In the case of glass, the etched substrate is transparent and thus allows the experimenter to view the pattern of skin deformation when the glass is moved over the skin. In the case of silicon, the etched, patterned silicon dioxide acts as a mask in the presence of a second etchant. This etchant can be either isotropic, or nonpreferential, which results in raised structures with curved sides, or anisotropic which preferentially etches the (100) crystallographic plane, producing microstructures with very sharp edges and straight sides. These various microstructures are useful in sensory and neurophysiological studies of the cutaneous perception of surface texture where it is necessary to control the shapes, sizes and spacing of the textural elements with a high degree of resolution. Microstructures of 25 μm size are readily produced with these techniques.*

Keywords—Cutaneous, Texture, Photolithography

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When the human hand is brought in contact with an object in the environment, there is usually a displacement of the object's surface across the skin. The cutaneous perception of texture requires such lateral movement, particularly for finely textured surfaces. Texture perception also requires a sufficiently high density of cutaneous receptors. The fingertips are particularly well suited for texture perception since these areas are frequently brought in contact with textures during active manipulation of an object. The cutaneous system that processes tactile information during such manipulations must be highly specialized to process temporal and spatial information generated by nerve impulse activity within the four types of low-threshold mechanoreceptive afferent nerve fibers innervating the human glabrous skin.[3,4,11,12,21,24,25]

One might ask how the shapes, sizes, and spatial organization of the elements making up a texture interact with the skin to produce patterns of action potentials in the population of first-order mechanoreceptive afferent nerve fibers. A second question is how the central nervous system processes the relevant information in this primary neuronal data base. Prior to answering these question, two technical problems must be solved. The first problem, and the subject of the present paper, is how to construct a series of surface textures that vary in surface geometry. The second problem is how to apply such textures to the skin with displacements and compressional forces that can be precisely controlled and varied from trial to trial. A solution to this second problem will be the subject of a companion paper wherein a new tactile stimulator is described.[15] The solutions to these two problems are required for studies in which parallel psychophysical and neurophysiological studies of texture perception using the same sets of stimuli are carried out.

In the present paper we describe techniques of contact photolithography which can be used to construct, from drawings generated by a computer, three-dimensional microstructures that are chemically etched into silicon or glass. These techniques were originally developed for the production of electronic integrated circuits. As discussed in greater detail in a number of references[5,9,23] they are commonly implemented with sophisticated and expensive equipment. We have, however, developed a set of procedures that are relatively simple and can be implemented without recourse to a full integrated-circuit laboratory. These procedures provide the neuroscientist with the capability of controlling the shapes, sizes and densities of the elements making up a texture. It is then possible to study how variations in the geometry of a surface texture are related to the tactual capacities of humans to detect, discriminate between, and identify such textures brought in contact with the skin. In parallel neurophysiological studies, it is also possible to study how certain physical characteristics of surface texture are translated into nerve impulse activity in cutaneous mechanoreceptors and how this primary afferent information is processed within the central nervous system.

METHODS

The methods described below are used to generate either a single element, such as an edge or a raised dot, or a texture consisting of an array of such elements. These patterns can be used in such experiments as the determination of the minimal height of an element or elements of a texture that can be detected by active touch with the fingertip.[10]

Producing a Mask with the Desired Pattern

The first step in contact photolithography[23] is to produce a mask containing the desired pattern. Patterns we have used consist of a single dot, dots or grids that are drawn with high-contrast black ink on mylar. In the case of complex patterns, such as dot arrays, requiring a large number of accurately placed elements, the pattern is drawn with a high-resolution plotter controlled by a PDP 11/34 computer. The desired patterns are reduced photographically (10:1 or 20:1) onto high contrast 35 mm film (Kodalith Ortho, Type 3). The developed film is then used as the mask, as described below.

Etching Patterns in Silicon

Silicon wafer substrates were obtained from General Diode Co. (Framingham, MA). These wafers are p-type, 1.5 inches in diameter, 0.011 inches thick, (100) orientation, chem-mechanically polished on both sides and 1-10 ohm-cm resistivity. Each wafer is cleaned in a series of steps using trichlorethylene, acetone, deionized water, methanol and concentrated sulfuric acid. The wafer is then thermally oxidized at 1000°C in steam for approximately 4 hours to form an SiO_2 film 1 μm thick (Fig. 1). (This SiO_2 film is used as a mask for etching the silicon.) Hexamethyl disilazane (HMDS) (PCR Inc., Gainesville, FL) is spun on the wafer at 3000 RPM using a "spinner" (Model HC101, Headway Research Inc., Garland, TX)* after which a positive acting photoresist (AZ-1370, Shipley Co., Newton, MA) is also applied by spinning at 3000 RPM. The HMDS facilitates adhesion of the photoresist to the SiO_2. It is probable that less precise methods of applying photoresist, such as manually dipping the wafer, might work as well as the spinning process.

The 35 mm film positive mask is then held against the photoresist by means of a "conformal device."[6,23] This instrument consists of four doughnut-shaped brass rings (together, about 3″ thick) which fit on top of each other and are held in place by a series of screws (Fig. 2). In the center of the window frame is attached a sheet of mylar. When using the confor-

*A spin on application of a silica film (Emulsitone Corp., Whippany, New Jersey) may be used instead of thermal oxidation to produce a suitable SiO_2 film.

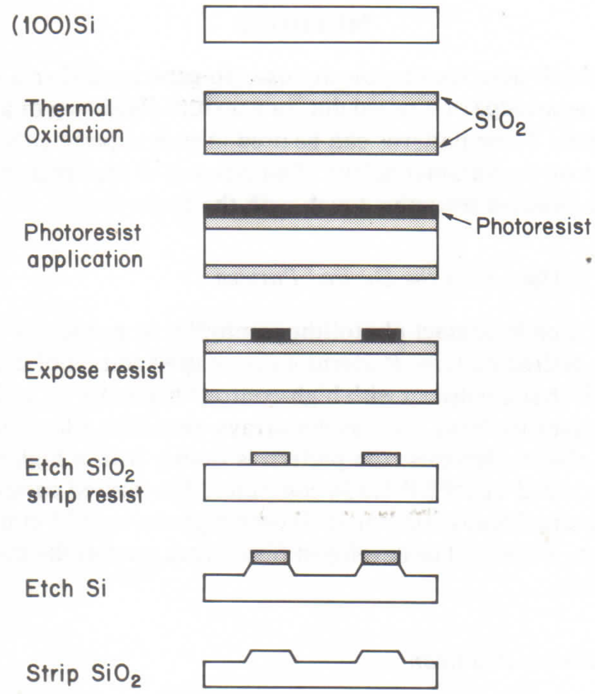

Figure 1. Summary of the method of contact photolithography used to etch a pattern into silicon. A silicon (Si) wafer, (100) orientation, is oxidized to form a layer of silicon dioxide (SiO_2) and then coated with photoresist. The photoresist is patterned by exposing it to light through a 35 mm flim containing the pattern. The photoresist acts as a mask during etching of SiO_2. The SiO_2 serves as a mask when etching silicon with an isotropic or anisotropic etchant. When etching a pattern in glass, the thermal oxidation step is bypassed, and the photoresist serves as the only mask.

mal device, the window frame is first removed and a glass plate, with the 35 mm photographic film taped to it (emulsion side up), is placed onto the sample holder. The wafer, coated with photoresist, is placed over the film (photoresist side down). The frame is then secured to the base. The conformal device is then evacuated through the vacuum pumping port, causing the mylar to conform to the wafer and press the wafer against the 35 mm film. The photoresist is then exposed with a bright light (an ordinary slide projector at a distance of about 8 inches) in order to expose the desired pattern in the photoresist. The exposure time is typically two minutes.

Next, the wafer is placed in developer (AZ-351, Shipley Co., diluted 5 parts deionized water to 1 part developer). The photoresist which was exposed to light is washed away by the developer. All steps through photoresist development are carried out in a "yellow" room in which the lights are shielded to eliminate blue and near-UV light.

The wafer is subsequently placed in a buffered oxide etchant (Allied Chemical Corp., Morristown, NJ) against which the unexposed resist acts as a mask (Fig. 1). After this, the photoresist is removed with acetone leaving the now patterned SiO_2. The patterned SiO_2 serves as a mask when the wafer is placed in silicon etchant.

We have used two types of silicon etchants. One is an isotropic etchant[2] consisting of 7 parts nitric acid (70%), 2 parts glacial acetic acid and 2

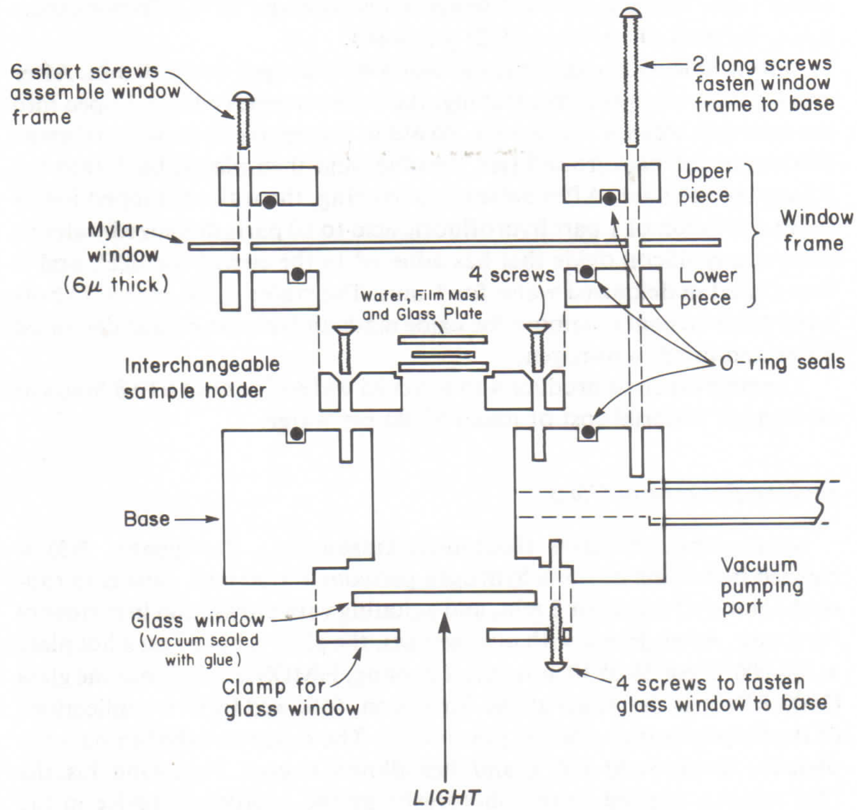

Figure 2. An exploded view of the conformal device used in the process of patterning photoresist-coated silicon or glass. A glass plate with the 35 mm photographic film taped to it (emulsion side up) is placed onto the sample holder. The silicon wafer (or glass) coated with photoresist is placed over the film (photoresist side down). When the chamber is evacuated, atmospheric pressure holds the mylar window, silicon wafer, conformal film mask and rigid workpiece in intimate contact. The exposing light is transmitted through the bottom glass window as indicated. The overall diameter of the conformal device is 5 inches.

parts (49%) hydrofluoric acid. This etchant etches all crystal directions at roughly similar rates (silicon is a single-crystal material). At room temperature the etch rate is 5 to 7 μm/min. The other type of etchant we have used is anisotropic, etching preferentially certain crystallographic planes, thereby producing microstructures with sharp edges. We use the ternary mixture of 250 g of potassium hydroxide, 250 ml isopropyl alcohol and 800 ml deionized water. This etchant attacks the (100) crystallographic direction about 100 times faster than the (111) direction since the (111) planes are much more densely packed at the crystal surface.[1,2] (Other known anisotropic etchants may be rather toxic if used without adequate precautions.) The literature suggests an etch rate in the (100) direction of about 1 μm/min at a constant temperature of about 80°C.[2] In our experience, the etch rate is about 1.25 μm/min.

During anisotropic etching, the solution is changed every 30 min. After every 20 min of anisotropic etching, the wafer is removed and dipped into the isotropic etchant for 2–3 sec, to aid in preventing formation of small hillocks in the background (see Results), and then placed back into the anisotropic etchant. After anisotropic etching, the wafer is dipped for 15 sec in a solution of 1 part hydrofluoric acid to 10 parts deionized water to remove any silicon oxide that has adhered to the etched surface[1], and is then rinsed in deionized water for 1 min. The wafer is last placed in buffered oxide etchant to remove the oxide mask and then washed in deionized water and dried in nitrogen.

The time taken to produce 4 to 6 etched wafers is about 6 to 8 hours at an average material cost of under $7.00 per wafer.

Etching Patterns in Glass

Microscope-slide glass (Becton-Dickinson Co., Parsippany, NJ) is cleaned by boiling in 7.5% hydrogen peroxide for 30 min, rinsing in running deionized water for 2 min, and agitating with ultrasound in methanol for 2 min. After drying with nitrogen gas, the glass is baked on a hot plate at 90–100°C for 20 to 30 min. After cooling, HMDS is spun onto the glass (3000 RPM) as described above for silicon, followed by two applications of the Shipley positive-acting photoresist. The substrate is baked on a hot plate for 20 min at 90–100°C and then allowed to cool. Following this, the film mask is applied to the photoresist by the conformal device in the manner described above. After exposure the glass is placed in developer, rinsed with deionized water, dried with nitrogen, baked at 135°C for 20 min, cooled and placed in the buffered oxide etchant against which the unexposed (patterned) photoresist acts as a mask. Finally, the glass is rinsed in deionized water for 2 min, stripped of photoresist in acetone under ultrasound agitation and rinsed again in deionized water. For a shorter duration of etching (e.g., less than 10 min), the etch rate is about 0.5 μm/min.

For reasons not yet clear to us, longer durations of etching, even when the etchant solution is periodically replaced, result in microstructure heights of no more than 10 to 15 μm.

Measurements of Etched Microstructures

The height of each structure was measured by one of two methods. An ordinary light microscope equipped with a scale monitoring the position of the objective lens relative the object table was used for measurements of microstructures of heights greater than 3 μm. By first focusing on the top of the structure and then focusing on the smooth background and reading the difference in the stage height, an estimate of the height of the structure was obtained. This procedure, repeated several times, provided an accuracy of about ± 0.2 μm. Microstructures of smaller heights were measured by means of an interferometer attached to a light microscope according to the method described by Nomarski and Weill.[22] The accuracy of the height measurement obtained with this method was about ± 0.05 μm.

RESULTS

Parameters Determining the Shape and Size of an Etched Microstructure

The shape and size of an etched element depends upon the size of the mask, the duration of etching, the type of etchant and the type of material etched. Also, if the etch mask erodes during etching, the profile will be affected—a condition one, in general, tries to avoid. For all types of etchants, the height of the etch element is directly related to the duration of etching within certain limits (see Methods). The diameter of the etched structure is always less than that on the etch mask due to the lateral etching beneath the etch mask. In the case of the isotropic etchant, the etch rate is the same in lateral and vertical directions and so the resulting decrease in diameter of an etched element from that of the mask should be equal to twice the height of the element. The anisotropic etchant etches about 100 times as fast in the vertical (100) plane than in the horizontal (111) plane.[2] Thus, the diameter of an anisotropically etched element is reduced by about 0.01 times its height.

In general, the height of an element used in this study was about 0.7 times its base diameter. This relation limits how closely spaced the elements can be for each height.

The mask patterns we have used to date have either been edges (half opaque and half clear on the 35 mm film), circular dots, or bars. Etched dots result in shapes roughly like truncated pyramids, the pointedness of which depends on the type of etchant used and on the diameter of the dot masks. Etched bars result in shapes roughly like truncated triangular prisms. More exactly, however, the side profile of an etched element is influenced by the type of etchant and the material etched. Figure 3 shows schematically the profiles of the etched slopes of a raised microstucture etched with isotropic etchant in glass and in silicon, and etched with anisotropic etchant in silicon. In the case of the glass, the angle between the flat surface and the slope is about 20°. The corresponding angle for structures etched in silicon with isotropic etchant is about 45°. In both of these cases, the slope is not a straight line, but rather a part of a circle with the radius somewhat greater than the etched height. The corresponding angle for bars (but not necessarily dots) etched in silicon with anisotropic etchant is about 54.7°,[1,2] and the edge profile can be described by a straight line. To achieve this exact angle, the bars must be oriented along the (100)

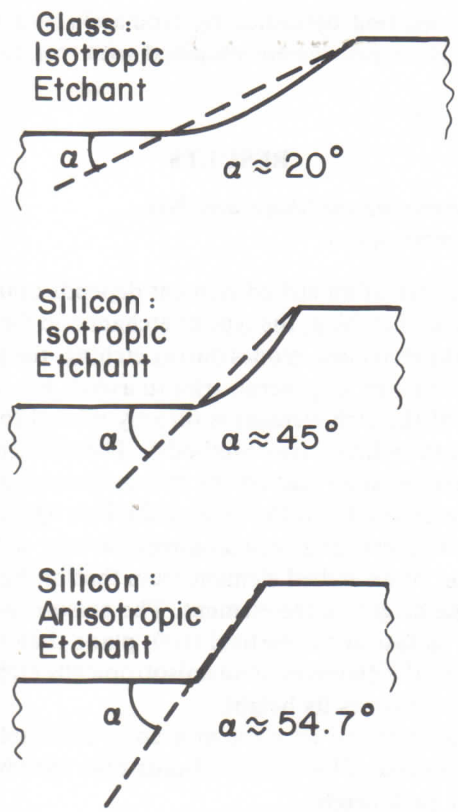

Figure 3. Schematic of the characteristics of the etched slopes of raised structures etched in glass and silicon with isotropic etchants and in silicon with an anisotropic etchant.

crystal direction, i.e., parallel or perpendicular to the wafer orientation flat. Thus, the dependence of slope on the combination of the type of material and the type of etchant gives us the possibility of manufacturing texture elements with different steepnesses of edge.

Anisotropically Etched Microstructures

The anisotropic etchant is useful in constructing large etched elements with smooth sides, each having the same side angle regardless of height and each having sharp corners. In Fig. 4 is a scanning electron micrograph (SEM) of trapezoidal dot structures etched in silicon. The exposure mask consisted of symmetrical rows of dark circles. A view of another set of dots etched from the same mask is shown in Fig. 5. The structures in Fig. 5 were first etched anisotropically. Then, following removal of the SiO_2 masks, the wafers were placed in an isotropic etchant which rounded off the sharp edges to produce mounds. The technique of rounding off edges might be useful as a means of controlling how well the edges of a microstructure "catch" the skin during lateral displacement of the finger over the texture.

A recurrent problem with the anisotropic etchant is the occasional formation of small hillocks, 5–10 μm diameter. When hillocks occur at a sufficient density within a region of the wafer, they are perceived as a subtle texture. The occurrence of this background texture is somewhat unpredictable, although such hillocks have been reported in studies of anisotropic etchants.[2] In some cases, hillocks can be eliminated by placing the wafer briefly into an isotropic etchant at intervals during anisotropic etching (see Methods). The presence of a background texture can pose problems in that it might serve as a sensory cue in experiments requiring sensory discriminations between etched structures that have small heights (e.g., 1–6 μm). Therefore, for such experiments, we have produced microstructures without hillocks by use of only an isotropic etchant. Isotropic etchants, as described in the following, produce a very smooth background.

Isotropically Etched Microstructures

The isotropic etchant is particularly useful for producing microstructures etched with a smooth background in cases where undercutting of the mask and straightness of the side profile are not crucial. An example of a raised circular dot etched isotropically in silicon is shown in Fig. 6. The minor irregularities in the top edge and side of the dot may arise in part from irregularities in the original drawing used to produce the photographic mask. It seems very unlikely that the presence or absence of such small irregularities would influence cutaneous sensation. More important is the fact that the photolithography procedures can produce microstruc-

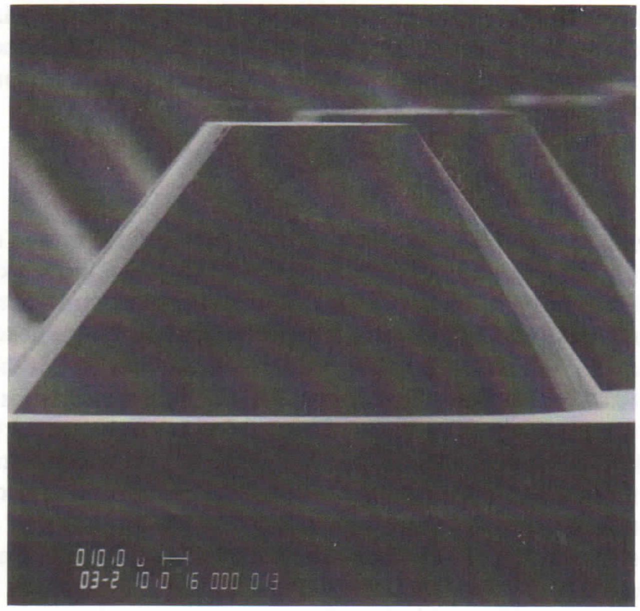

Figure 4. A scanning electron micrograph (SEM) of circular trapezoidal structures etched in silicon with anisotropic etchant. A 10-μm size bar is shown.

tures having smooth and flat tops against a background surface that is also very smooth and flat. It would also be possible to round the top edges by removing the SiO_2 masks and etching again isotropically.

Precise topography measurements of the surface roughness and the profiles of microstructure elements, such as that shown in Fig. 6, were made for several of our *isotropically* etched silicon wafers by the National Bureau of Standards. In Fig. 7 there is a direct reading of the height of the stylus of a profilometer as it was moved over a single raised dot. This particular dot is one of a series used to measure tactile detection thresholds.[10] The height of this dot, as indicated by the profilometer record, was about 2.4 μm. This is within 0.2 μm of the value we obtained by means of an interferometer (see Methods). This particular dot was surrounded at its base by a small trough about 50–80 μm wide and 1 μm deep. We do not know the origin of this trough. Surface roughness, R_a, was measured as the mean absolute deviation of the surface profile from a mean reference line through the profile. The R_a value was obtained from each of 6 horizontal tracks, each 1.5 mm long, and each track within the area around the raised dot that came in contact with the finger during the tactile detection experiments. The average R_a was 0.0071 μm $\pm$ 0.002 μm (SD). The grand average obtained from 3 different wafers was 0.014 $\pm$ 0.0096 μm. These surfaces

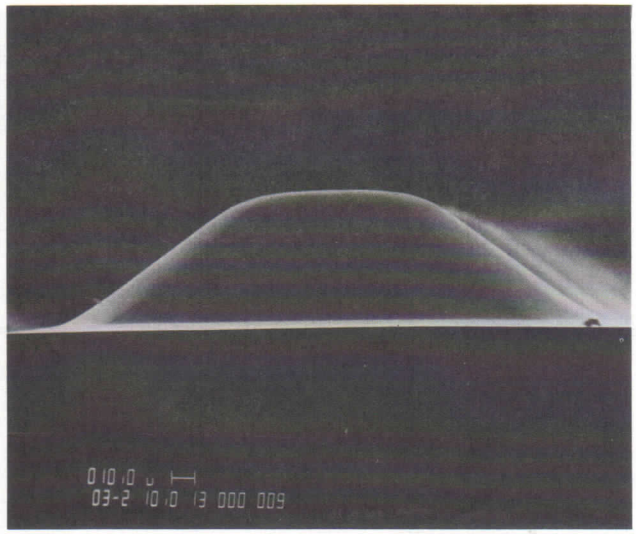

Figure 5. An SEM of circular "mounds" etched in silicon. These were patterned with the same 35 mm film mask of closed circles as was used for the structure in Fig. 4. The mounds were etched first by the anisotropic etchant to produce structures with sharp edges and straight sides, as in Fig. 4. Subsequently, the oxide masks were removed by buffered oxide etchant and the wafer then placed in isotropic etchant which rounded off the edges and reduced the slopes of the sides of each raised structure to produce mounds. A 10-μm size bar is shown.

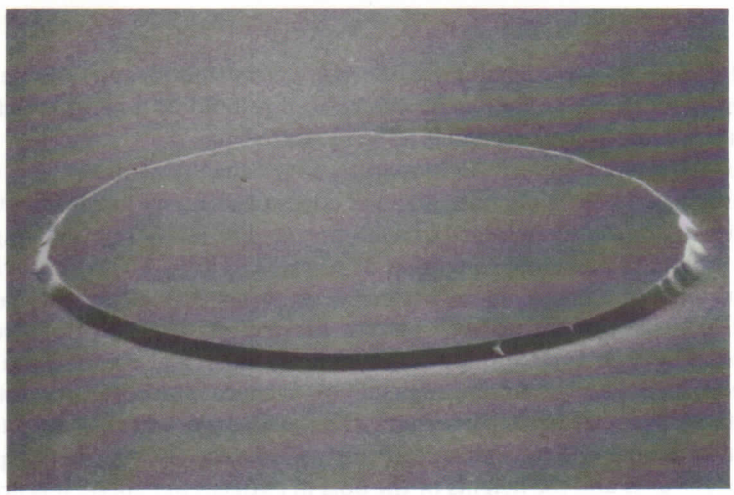

Figure 6. SEM of a raised circular dot etched isotropically in silicon. The diameter and height of the dot are 541 μm and 11 μm respectively.

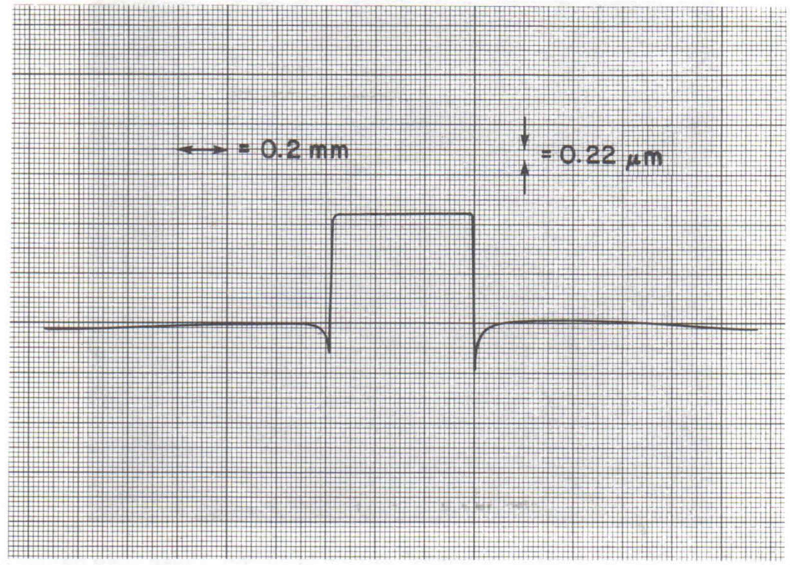

Figure 7. The path of a profilometer stylus as it was moved over a raised dot etched in silicon. The tip of the stylus was conically shaped with an included angle of 90 degrees and tip radius of about 2 μm. A computer sampled 4000 points spaced 0.375 μm along the measured profile for a sample length of 1.5 μm. As indicated, the height of the dot was 2.4 μm, its sides steep, and both the top of the dot and the background around the dot smooth and flat. (Note the differences in scale for the horizontal and vertical axes.)

produced by isotropic etching are, therefore, very smooth and suitable for experiments in which the tactile detection threshold of a microstructure against a smooth background is to be measured.

Aside from studies of the human sensory capacity to detect and discriminate between single raised dots or edges of different heights,[10] other studies are currently being conducted on the discrimination and magnitude scaling of perceived roughness of patterns of dots. Figure 8 provides an example of a homogenous pattern of elements that is currently being used in studies of texture and pattern perception. This texture is composed of dots arranged in a hexagonal array such that the distance between each dot and its six closest neighbors is equal. The density of dots in this sample pattern is 102 dots/mm^2, and the diameters and the heights of the individual dots are 33 μm and 10 μm respectively. By varying the spacing of the dots and the heights of the dots in patterns like these, it is possible to study the contributions of these variables to the perception of surface roughness. One might also vary the type of pattern from that of a random distribution of dots at one extreme to a highly regular pattern on the other extreme. Likewise, it is possible to manufacture gratings, of various spacings and heights, and other more complex patterns such as raised letters that could be used in studies of the tactile processing of spatial information. Our current technique for making 35 mm film masks achieves at best only a 3 to 5 μm lateral resolution; however, photolithography patterning itself is capable of submicron resolution, to about 0.2 μm with suitable masks.[7,23] Thus, very fine-scale patterns can be produced. For pattern dimensions <10 μm, chrome-on-glass masks are preferred over 35 mm film.

An obvious advantage of using microstructures etched in glass for studies of tactile mechanisms is that the interaction between the structure and the skin can be viewed and recorded through the glass by means of a microscope and camera. This makes it possible to relate the exact position of the microstructures to the receptive fields of cutaneous sensory neurons. It might also be possible to measure the lateral deformation of the skin produced by certain microstructures. In Fig. 9 is a photomicrograph of a glass plate with a dot of 600 μm diameter, 12 μm height, in contact

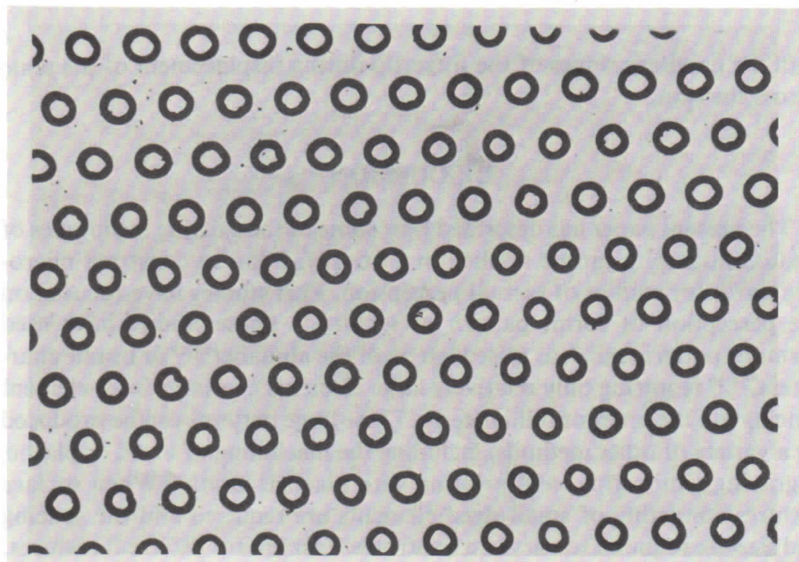

Figure 8. Photomicrograph of the top view of an homogeneous texture consisting of an array of raised dots etched in silicon. Each dot is about 33 μm diameter (top) and 10 μm height and equally spaced from its 6 nearest neighbors by 104 μm (center-to-center). The top surfaces of these dots are flat and constitute the only unetched parts of the silicon wafer. The diameter of the base of each dot (outer diameter of the dark circle) is larger than that of the top (light circular area) indicating the existence of a sloping edge, as expected.

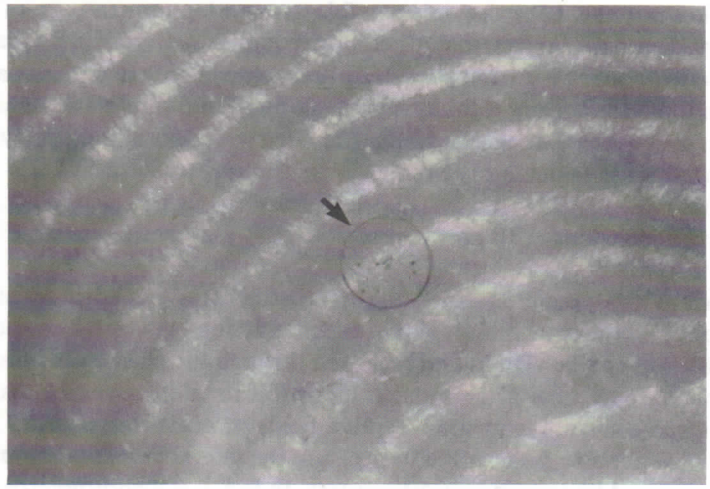

Figure 9. Photomicrograph of a single raised dot in a glass plate that was automatically brought onto the tip of a human finger by the tactile stimulator. The dot (arrow) is 600 μm in diameter and 10 μm in height.

with the papillary ridges of the fingertip during displacement of the plate across the skin.

DISCUSSION

The present paper has described how some of the existing techniques of photolithography can be applied in a novel fashion to construct microstructures for studies of tactual perception. Past studies have focused on the perception of form, pattern or texture.[17] These studies have used forms or patterns, such as raised letters of the alphabet[13,19] or braille characters,[12,20] requiring only relatively large elements and large inter-element spacing (on the order of millimeters). These large patterns can be produced by a variety of other methods, including the machining of metal or plastic, engraving, embossing, and printing with plasticized ink.[8] When surface textures consisting of small sized-elements are required and the spacing and size are required to vary in a controlled fashion for different textures, then the number of techniques available is limited.

Most studies of texture perception have been of surface roughness in which such stimuli as paper surfaces, varying in smoothness, or sandpapers of varying roughness, have been used. Use of such commercially available materials has drawbacks, however, since the experimenter may not be able to control the shape, size and spacing of elements comprising each texture. In addition, the reproducibility of the surface texture of commercially produced materials cannot be guaranteed. Also, commercially available surfaces may evoke multiple qualities of cutaneous sensation. For example, since the elements of sandpaper are jagged, they evoke sensations of varying degrees of "sharpness" as well as roughness.[17,26]

The studies of Lederman and her colleagues[16-18] represent the first and certainly the most extensive attempt to *construct* simple textures for the purpose of relating variations in the surface geometry to textural perceptions, in this case perceived roughness. The stimuli were machined, grooved aluminum alloy plates that could be made to vary in steps of 125 μm in the width of grooves and of the "land" between grooves. The presence of asperities and irregularities of small dimensions, and the inability to control the sharpness or roundedness of edges, may cause problems in certain experiments during the application of these textures to the skin. Also, the edge definition produced by a milling machine or even the more versatile wire electric discharge machine is limited. Lastly, machined elements cannot be made as small or placed as closely together as those produced by photolithography techniques.

Recently, Darian-Smith and his colleagues[3,4] and Johnson and Lamb[12] have used stimuli consisting of raised dots or bars etched in nyloprint to study the response properties of mechanoreceptors and the capacities of humans to discriminate between and recognize tactile patterns and textures. The use of a nyloprint pattern is more versatile in some respects than the use of machined surfaces, such as used by Lederman, since elements with small diameter and small height can easily be made to precise specifications from a photographic mask made from an ink drawing. A drawback of the photolithographic method based on nyloprint, as well as those used to produce braille and other materials for commercial use, is that the experimenter must rely upon a highly stereotyped industrial process that often cannot be conveniently modified. Further, such processes do not have sufficient resolution in cases where it is necessary to produce elements of very small diameter and height as required, for example, for the study of tactile detection thresholds as a function of microstructure height.

There are several advantages of the photolithography procedures outlined in the present paper. First, microstructures can easily be constructed in the laboratory. The major requirements are a relatively clean room with yellow lighting (to prevent exposure of photoresist by blue light), a source of deionized or distilled water, a high-speed spinner, a microscope, and standard 35 mm photographic equipment. The ability to construct and examine microstructures in the laboratory setting allows the experimenter great freedom to modify each microstructure to suit the ever changing requirements of an experiment. Further, the photolithography techniques we have described allow the sizes and spacing of raised elements, and to a great extent, the overall shapes of these elements, to be controlled. There are also many variations in the techniques that have yet to be explored, such as the use of multiple applications of masks and photoresist to produce elements of different heights within the same microstructure. For example, one might study the perception of a "signal" consisting of one higher element against a background of "noise" or elements of lower height. Finally, microstructures can be made directly from photographs of artwork that can either be drawn by hand or, in the case of more complicated patterns, drawn by a computer driven plotter. With computer generated drawings it would be possible to produce textures that do not resemble either those created by nature or by the commercial industry. Such patterns may reveal aspects of sensory processing which might otherwise go unnoticed as was the case for Julesz's random dot stereograms for visual depth perception.[14] It may also be possible to make textures that provide discriminable signals only to one class of cutaneous receptors and random noise to all the others. Such textures might prove useful in clinical tests of somatosensory function.

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EQUIPMENT SOURCES

1. Allied Chemical Corp., P.O. Box 1087R, Morristown, NJ 07940
2. Becton-Dickenson & Co., Parsippany, NJ 07054
3. Emulsitone Co., 19 Leslie Court, Whippany, NJ 07980
4. General Diode Corp., 90 Eames St., Framingham, MA 01701
5. Headway Research, Inc., 713 Forest Lane, Garland, TX 75040
6. PCR Inc., P.O. Box 1466, Gainesville, FL 32602
7. Shipley Co., Inc., 2300 Washington St., Newton, MA 02162