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3D-Nanomachining using Corner Lithography

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Abstract— **We present a fabrication method to create 3D nano structures without the need for nano lithography. The method, named "corner lithography" is based on conformal deposition and subsequent isotropic thinning of a thin film. The material that remains in sharp concave corners is either used as a mask or directly as structural material. The method is demonstrated for nano scale modifications of pyramidal tips, as well as the creation of suspended nanowires.**

Keywords- corner lithography; nanomachining; 3D; tip; SPM

I. Introduction

Several fabrication strategies have been developed to define sub-micron features without the need for nano lithography. These include edge lithography to create 2D-confined nanochannels [1] and nano-ridges [2], the use of stress induced retardation of oxide growth in corners to create nano-apertures [3], and low temperature oxidation and selective etching (LOSE) to create an aperture at the apex of a pyramidal tip [4].

Corner lithography was introduced in [5] and used to create a nano wire pyramid. The present paper extends this work and three new structures are shown that are based on corner lithography. Corner lithography is based on the material that is left in sharp concave corners after conformal deposition and isotropic etching (fig. 1). If t is the thickness of the deposited layer, α is the angle of the sharp concave corner, and R is the isotropic thinning distance, then the remaining material has a thickness w (see fig. 1), given by:

$$w = a - R = t / \sin(\alpha/2) - R \qquad (1)$$

The remaining material in the corners are refered to in IC fabrication as "stringers" and are usually considered undesirable. In corner lithography they either constitute the structural material of wire structures and tips, or are used as a masking material in subsequent fabrication steps. The general fabrication method consists of a few basic steps: (1) mold fabrication, (2) conformal deposition of the structural material, (3) isotropic thinning of the structural layer, nanowires remain in sharp concave corners and (4) removal of the mold. From the examples presented in this paper it will become clear that several steps can be added, for example to create an inversion mask. As will be shown the presented method is a powerful technique for nano-patterning of pyramidal tips, as the ones used in scanning probe microscopy (SPM).

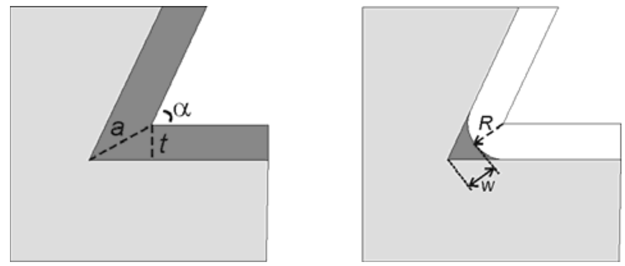

Figure 1. Illustration of the thickness w of the remaining structure in corner lithography. t Is the thickness of the deposited layer, α is the angle of the sharp concave corner, and R is the isotropic thinning distance.

II. Experimental

A. Materials and Etchants

The materials mostly used in our experiments as structural or masking material are polysilicon (Low Pressure Chemical Vapour Deposited, LPCVD), silicon oxide (thermal), and low stress (silicon rich) silicon nitride (LPCVD). Table 1 summarizes the etch rates of these materials in the etchants used in the experiments. TMAH refers to a 5 wt% solution of tetramethyl ammonium hydroxide in water at 70 °C. 50% HF etching is performed at room temperature, without stirring. H_3PO_4 refers to a 85 vol% solution at 180°C.

B. Pyramid with Metal Nano-Tip

The aim of this experiment was to create an insulating micro pyramid, with metallic tip. Ultimately this type of structure could find application in advanced SPM, for example for localized electrical or electrochemical measurements. Fig. 2 shows the fabrication scheme for an oxide pyramid supporting a nano scale metal tip. Fabrication started with the mold fabrication, in this case by KOH etching in a <100> silicon wafer to create the pyramidal hole bounded by the <111> planes. Next, silicon nitride (220 nm) was deposited by

TABLE I. Etch rates of materials used in different etchants. Etch rates in nm/min

Etchant	Material		
	Polysilicon	Silicon nitride	Silicon oxide
TMAH	4-7e+02 *	1e-02	7e-02
HF 50%	4e-02	3.3e+00	2e+03
H_3PO_4	3e-01	4.3e+00	2.5e-01

*The lower value is for the lateral etch rate in confinement, specifically for the conditions presented below. The higher value is for the blank film.

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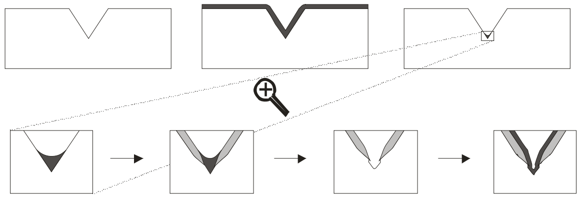

Figure 2. Fabrication scheme for the silicon oxide pyramid containing a nano scale metal tip.

LPCVD (conformal deposition) and isotropically removed in 50% HF (84 min. at room temperature). This is a timed etch step which required a 1.23 times over-etching to remove the silicon nitride in the four oblique ribs of the pyramidal hole (α = 109.4°) and leaving only a small piece of silicon nitride at the tip. To calibrate the etching speed, a dummy wafer containing the same thickness of silicon nitride was etched in parallel. The silicon oxide structural material for the pyramid was formed by local oxidation of the silicon (LOCOS) [6] using the residual silicon nitride as the inversion mask. The LOCOS step was a wet oxidation performed at 1000 °C for 35 min., resulting in a 270 nm layer. Next, the silicon nitride at the tip was removed in hot H_3PO_4 (30 min. at 180 °C) and 30 nm Chromium was deposited by sputtering to create the metal tip. Finally, the silicon mold was removed in TMAH. TMAH is a suitable etchant for this step as it has a high selectivity for silicon as compared to silicon oxide (table 1) [7]. Fig. 3 shows the fabricated silicon oxide pyramid having a Chromium tip of less than 300 nm in size.

C. *Pyramid with Nano-Apertures*

The aim of this experiment was to create a pyramid with tunable nano apertures close to the tip. Fabrication started with KOH etching of the pyramidal mold in a <100> silicon wafer. Next, 500 nm LPCVD silicon nitride structural material was conformally deposited, followed by 330 nm LPCVD polysilicon. This layer acted as etching mask in later steps. A second layer of silicon nitride (120 nm) was deposited and isotropically etched in 50 %HF in order to remove all of the silicon nitride but a small remnant at the tip (fig. 4a). This remnant was used as an inversion mask in the LOCOS step (wet oxidation at 900°C for 10 min.) of the polysilicon (fig. 4b). After removal of the silicon nitride remnant a timed etching of the polysilicon followed, which starts at the apex of the pyramid and moves up along its sides (fig. 4c). The duration of this step determines the height of the nano apertures to be formed. Typically, a confined layer of 330 nm polysilicon etches laterally at a speed of $4.2 \cdot 10^2$ nm/min. in the 5 wt% TMAH solution supplied through a silicon oxide pinhole of sub 100 nm. Next the silicon oxide was removed and the first silicon nitride etched in 50% HF. This also is a timed etch step as it should leave the silicon nitride nano wires and the tip (fig. 4d). Fig. 5 shows a typical fabrication result with apertures in the order of 1 μm in size. The size and the location of the apertures can be tuned by the thickness of in particular the silicon nitride layers and by the polysilicon etching time.

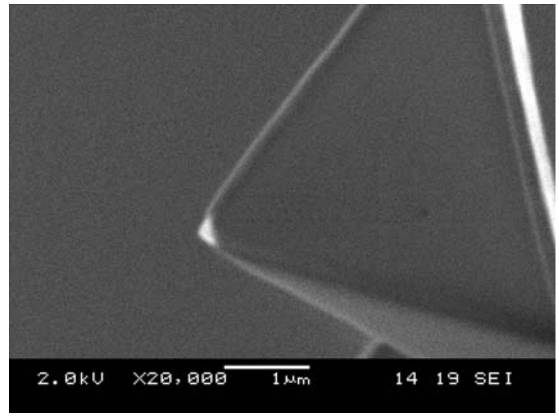

Figure 3. Silicon oxide pyramid containing a Chromium tip.

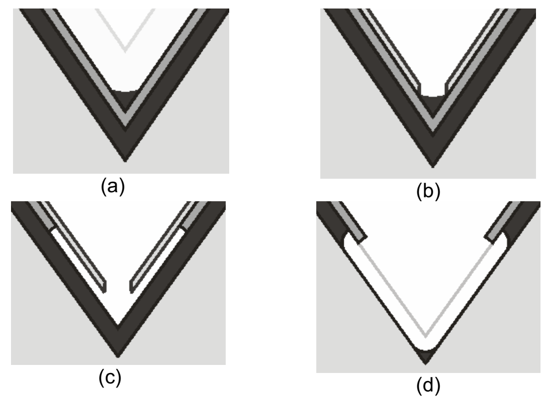

Figure 4. Visualization of the fabrication scheme for the silicon nitride pyramid with nano-apertures.

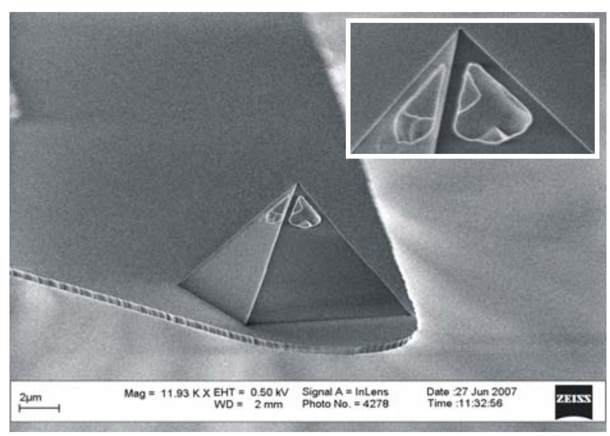

Figure 5. Silicon nitride pyramid with apertures in all four side walls.

D. *Nano Fencing: Suspended Nanowires*

In this experiment vertical nanowires and suspended horizontal silicon nitride nanowires were created in the sharp concave corners of a silicon oxide mold. The suspended nanowires illustrate the ability to create relative long, slender and rather complex 3D-structures using corner lithography.

To create vertical nanowires a silicon oxide mold was made containing the appropriate sharp concave corners. We illustrate the process which was followed by a hypothetical structure of four vertical wires created in the corners of a square mold. First a square silicon pillar is etched by Deep Reactive Ion Etching (DRIE) with photoresist as the mask material. Next, the resist is stripped and the wafer oxidized (wet oxidation at 950 °C) to form the silicon oxide mold (thickness of about 400 nm), fig. 6a. Under these conditions convex corners in the silicon are sharpened as is illustrate by the cross section, fig. 6b [8]. Finally, the silicon oxide is removed from the top by a maskless directional RIE step (fig. 6c), and the mold is hollowed out by isotropic RIE in a SF_6 plasma (fig. 6d). This completes the mold fabrication. To create vertical wires a silicon nitride layer of 350 nm was deposited by LPCVD and etched back in hot H_3PO_4 for 83 min to leave the wires in the concave corners. Finally, the silicon oxide mould was removed in BHF and the vertical nanowires remained (fig. 7). Note that vertical nanowires are only formed in concave corners of the mold, therefore they are situated only at convex corners of the supporting structure after removal of the mold.

To add suspended horizontal nanowires an overhanging “roof” is added to the mold to create an horizontally oriented concave corner. The fabrication of the mold is illustrated in fig. 8. First a silicon pillar is etched by DRIE (Bosch process) using a silicon oxide and silicon nitride bi-layer as the mask. Next, the silicon oxide is etched in BHF, under-cutting the silicon nitride thin film. Then the silicon nitride is thinned down in hot H_3PO_4 until it is only left on top of the silicon oxide. Using the remaining mask material a LOCOS step is performed. After stripping of the silicon nitride and thinning down of the silicon oxide, the silicon is isotropically etched in a SF_6 plasma through the window in the silicon oxide. Fig. 9 shows a SEM picture of a typical mold structure. The cross section next to it shows the location of the horizontal nanowires in the concave corners of the mold. Fig. 10 shows the resulting suspended nano wire structure formed after conformal deposition of silicon nitride (350 nm by LPCVD), subsequent isotropic thinning of this layer in hot H_3PO_4 for 83 min., and removal of the mold in BHF .

III. CONLUSIONS

We have shown a fabrication process for sub-micron structuring without the need for nano lithography. It is named corner lithography and is based on the material that is left in sharp concave corners after conformal deposition and isotropic etching. The process is capable of creating nanowires (vertical as well as suspended horizontal) and has been shown effective for modifications of pyramidal tips, as the ones used in scanning probe microscopy. As it is a batch-wise process, corner lithography is a relative cheap process that may lead to economically viable nano-structured components.

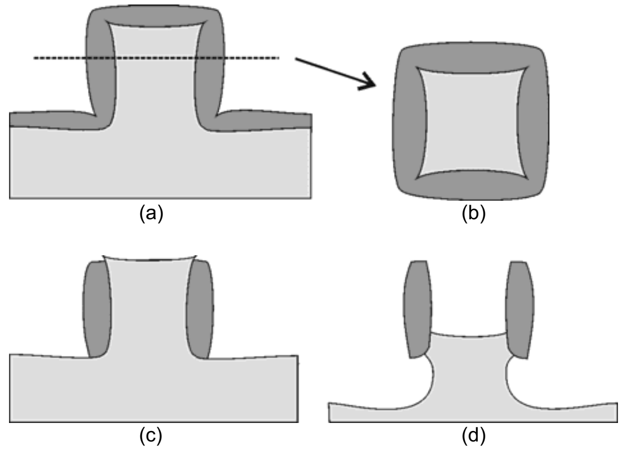

Figure 6. Mold fabrication for vertical nanowires. (a) Silicon pillar formation and oxidation. (b) Cross section showing the corner sharpening. (c) Anisotropic silicon oxide etching. (d) Hollowing out of the mold structure.

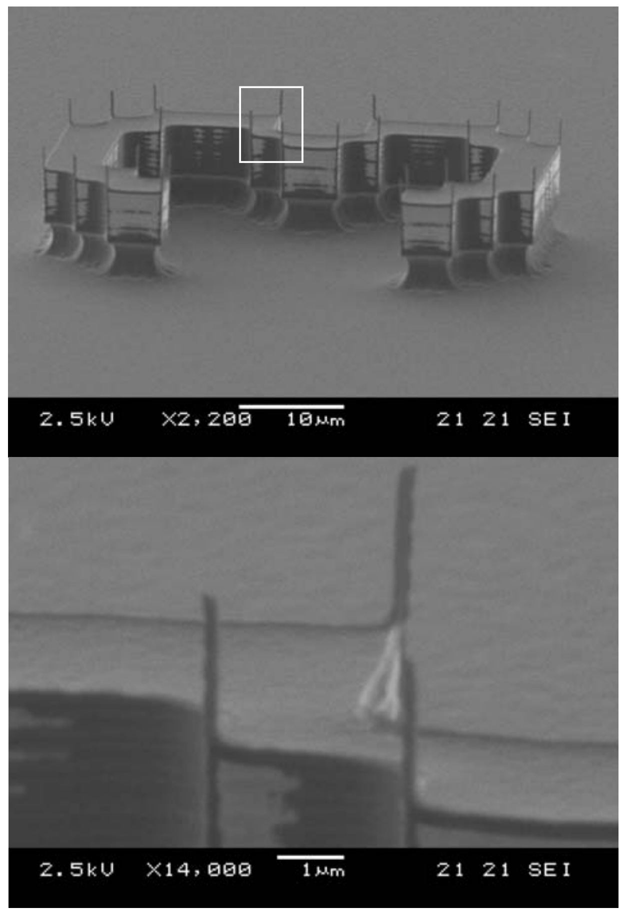

Figure 7. (Top:) Structure containing vertical nanowires created through corner lithography. Note that wires have only been formed in the concave corners of the mold. (Bottom:) Close up of some of the vertical nanowires.

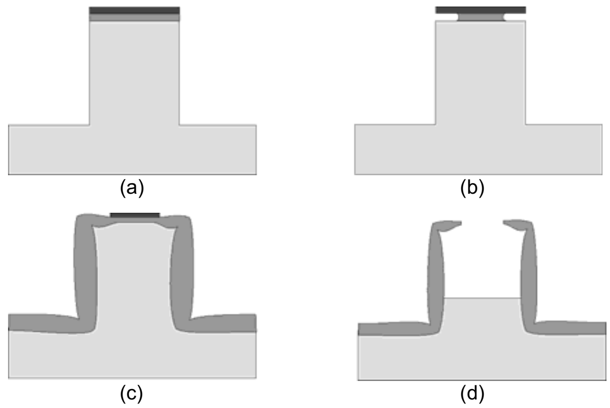

Figure 8. Mold fabrication for horizontal nanowires suspended by vertical nanowires. (a) Silicon etching. (b) Under cutting the silicon nitride mask layer. (c) Thinning down of the silicon nitride and subsequent LOCOS step. (d) Isotropic etching of the silicon to form the hollow mold structure.

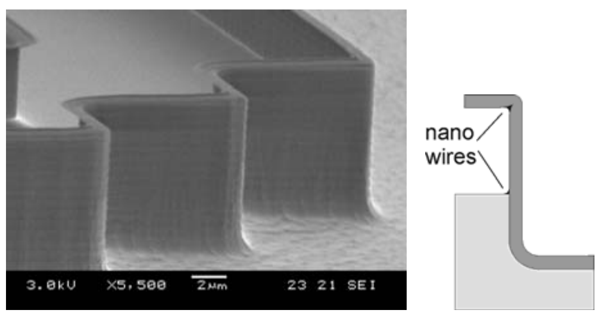

Figure 9. Silicon oxide mold, note the overhanging "roof".

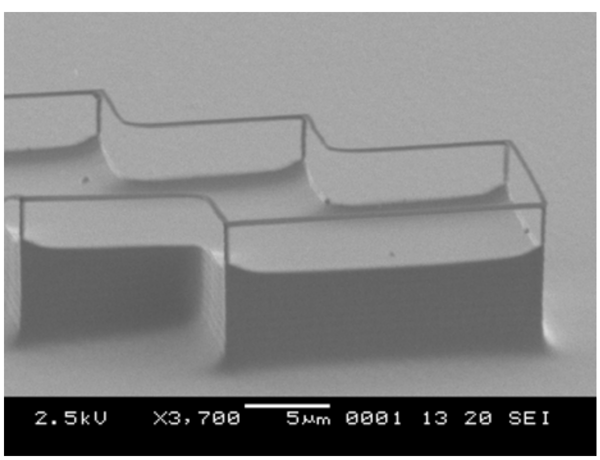

Figure 10. Suspended silicon nitride nano wires created by corner lithography.

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