Scanning probe lithography tips with spring-on-tip designs: Analysis, fabrication, and testing

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This letter reports a special tip design for probes used in scanning probe lithography applications. The sidewalls of the pyramidal tip located at the distal end of a cantilever probe are modified to contain folded spring structures to reduce the overall force constant of the scanning probe. The spring structure is generated using focused ion beam milling method. We have conducted finite element simulation of the force constants of such folded springs under various geometries. We also demonstrated sub-100 nm scanning probe lithography using a modified spring tip in the dip pen nanolithography writing mode. © 2005 American Institute of Physics. [DOI: 10.1063/1.2006210]

Scanning probe microscopy (SPM) has been widely used for surface characterization and modification. It is well known that the scanning probes used in SPM instruments can modify substrate surfaces through mechanical, electrical, or optical approaches. This has led to a rapidly emerging research field—scanning probe lithography (SPL). For example, dip pen nanolithography (DPN) is an additive SPL method. It uses a pre-coated cantilever tip to transfer “ink” molecules onto a substrate. It is uniquely capable of directly patterning many materials (e.g., organic molecules, biomolecules, metal salts, polymers, and nanoparticles) at molecular level.

In all cantilever-probe-based SPL methods, the probe consists of a cantilever with a sharp tip at its distal end, with the cantilever serving as a spring. The mechanical structure of the cantilever determines the stiffness of the probe and consequently the contact force between the tip and the substrate surface. The force constant of the cantilever, \( k \), is

\[
k = \frac{Ewt^3}{4l^3},
\]

where \( E \) is the modulus of elasticity of the cantilever material, and \( w, t, l \) are the width, thickness, and length of the rectangular cantilever, respectively. A desired force constant of a cantilever can be reached by trading off the width, length, and thickness parameters of the cantilever. As an example, DPN operation has been conducted using commercial silicon (Si) or silicon nitride (Si\(_3\)N\(_4\)) atomic force microscope atomic force microscope (AFM) probes, with their force constants usually in the range of 0.01–5 N/m. An overly soft probe tip can adhere to the writing surface, whereas an overly stiff one may result in mechanical scratches in the contact mode. For force constant in this range, if the thickness and width of a Si\(_3\)N\(_4\) cantilever are fixed (e.g., \( t = 1 \) \( \mu \)m, \( w = 30 \mu \)m), the length of the cantilever must range from 540 to 68 \( \mu \)m.

The motivation of this work stems from the need to produce high-density, arrayed SPL probes, especially two-dimensional (2D) arrays. The length of the cantilever dictates the minimal tip-to-tip spacings. The finite length of individual cantilevers will limit the achievable density of tip arrays.

To solve this problem, we present a type of probe tip with integrated spring structures. Figure 1 shows two tips with the spring-on-tip (SOT) designs. The tip may consist of 1–4 springs, each occupying one facet of the tip. Selected faces can be completely removed to reduce the number of

FIG. 1. Scanning electron microscopy (SEM) images of Si\(_3\)N\(_4\) SOT tips: (a) a tip with all four sides etched to identical profile, which can be considered as a tip supported by four identical springs connected in parallel; (b) a different profile of a spring tip where the tip is effectively supported by one spring connected to the probe cantilever.
springs (see an example in Fig. 2). Alternatively, spiral springs may be made [Fig. 1(b)].

The fabrication process for the tips is discussed here. First, pyramidal tips with continuous surfaces were made using Si$_3$N$_4$ film. Many practical methods for realizing pyramid tips have been demonstrated in the past. This current method can be used on tips made using a variety of thin film materials. The spring structures are created afterwards on the pyramidal tip using focused ion beam (FIB) milling (etching) method. The FIB milling width can be varied from nanometer to micrometer scale by adjusting FIB parameters.

In order to optimize the spring design at the tip, an analytical model combined with finite element analysis is used to evaluate the force constant. It is assumed that the pyramidal tip has four sidewalls with identical spring structures. In this case, the tip can be considered as supported by four springs with equal spring constants ($k_t$) connected in parallel. The force constant of the SOT tip ($k_t$) is the sum of the four spring constants

$$k_t = 4k_s.$$  \hspace{1cm} (2)

A SPL probe (or even a SPM probe for this matter) can use both traditional cantilever spring and the SOT springs simultaneously. The overall force constant of the tip is distributed to two independent parts: the probe cantilever and the folded springs on tip. In this case the entire probe can be considered as these two spring systems connected in series, as shown in Fig. 3. The design of the cantilever and tip can be conducted separately. The overall force constant of the probe ($k_p$) can be determined by the spring constants of the cantilever ($k_c$) and the tip ($k_t$)

$$k_p = \frac{1}{\frac{1}{k_t} + \frac{1}{k_c}} = \frac{k_t k_c}{k_t + k_c} = \frac{4k_s k_c}{4k_s + k_c}.$$  \hspace{1cm} (3)

The spring constant of the SOT tip ($k_t$) is difficult to evaluate using analytical method due to its complex shape and loading conditions. The best way to obtain this spring constant is through finite element simulation.

Three-dimensional (3D) models were made based on actual dimensions of microfabricated tips for simulation. In 3D modeling, one facet of the tip is extracted and modified into a spring shape. Then the deformation of the tip under a concentrated force is simulated using the ANSYS finite element simulation software to determine its force constant. Among many possible spring designs, one representative result is discussed here. As shown in Fig. 4, a Si$_3$N$_4$ tip facet is cut into a spring shape by 12 $0.5\times10^{-6}$-wide FIB strokes. The film thickness is 0.9 $\mu$m. In the simulation, the two cross-sectional sidewalls of the facet are constrained to deform only in the vertical directions. The bottom plane of the facet is fixed in all directions. The dimensions and the simulation result of the facet are shown in Table I. When a 1 $\mu$N force is applied at the tip vertically (pointing down), the ANSYS simulation yields a vertical tip displacement of 3.47 $\mu$m, giving a spring constant of 0.288 N/m. The force constant of a tip with four sidewalls is 1.15 N/m according to Eq. (2).

By adjusting the Si$_3$N$_4$ film thickness and the FIB milling size and number, smaller force constants can be achieved. For example, if the film thickness in the tip design of Fig. 4 reduces to 0.3 $\mu$m, an ANSYS simulation has yielded a vertical displacement of 12.26 $\mu$m under 1 $\mu$N force applied at the tip (Table I), corresponding to a force constant of 0.082 N/m for one sidewall of the SOT tip. A tip consisting of four identical spring sidewalls thus has a force constant of 0.32 N/m. The simulation results show that the folded springs alone can provide proper spring constants for selected SPL applications (e.g., DPN).

**TABLE I. ANSYS simulation results for SOT tip designs.**

<table>
<thead>
<tr>
<th>Input and output parameters</th>
<th>1st tip design</th>
<th>2nd tip design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si$_3$N$_4$(^a) film thickness ($\mu$m)</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Tip height ($\mu$m)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Width of tip at bottom ($\mu$m)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>FIB milling number</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>FIB milling width ($\mu$m)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Applied force at tip ($\mu$N)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vertical displacement of tip ($\mu$m)</td>
<td>3.47</td>
<td>12.26</td>
</tr>
</tbody>
</table>

\(^a\)An elastic modulus of the 225 GPa and a Poisson’s ratio of 0.23 are used for the Si$_3$N$_4$ film material in the simulation (see Ref. 14).
The effective reduction of the SPL tip force constant by FIB milling leads to the possibility of utilizing cantilever-less tip arrays for high-density one-dimensional or 2D SPL patterning. In theory, arrays of SPL tips can be made closer to each other without supporting cantilevers.

The linewidth of FIB milling is a function of materials, ion beam current, dwell time, and operating voltage. Using an FEI Dual-Beam DB-235 FIB/scanning electron microscope (SEM), we have achieved minimal linewidth of 20 nm using 1 pA ion current operated at 30 keV. A large milling linewidth can be achieved with high ion current. The SOT tip shown in Fig. 1(a) required about 10 min to etch all sides. It is envisioned that the FIB etch time can be reduced in the future with increased experiences and through software automation of FIB milling tools.

To verify the functionality of the tips after FIB milling, SOT tips were used for DPN writing. A Si$_3$N$_4$ cantilever SOT tip similar to the one shown in Fig. 1(a) is used. The tip is mounted on a Thermomicroscopes AutoProbe M5 AFM.

The tip is inked with 1-octadecanethiol (ODT) ink, using techniques discussed elsewhere. After inking, the tip is brought into contact with a gold-coated silicon substrate for DPN writing. ODT line patterns have been successfully generated by moving the tip on the substrate at different speeds. Figure 5(a) shows a lateral force microscopy (LFM) image of three ODT lines generated on a gold surface with writing speed of 0.1, 0.2, and 0.3 μm/s. The linewidth is 175, 120, and 95 nm, respectively. Increased writing speed results in decreased linewidth [Fig. 5(b)], as expected. The linewidth tends to saturate at 43 nm (at writing speeds of 0.9 and 1 μm/s), probably due to the relatively big curvature radius of the tip (~0.9 μm).

In conclusion, this letter introduces a spring-on-tip structure for scanning probe lithography. Conventional cantilever tip can be converted to SOT tip using focused ion beam milling. An analytical method combined with finite element analysis has been used to model the force constant of the SOT tip, or a cantilever with an SOT tip located at its distal end. The SOT tip has been successfully used for demonstrating DPN nanolithography.

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