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Microfabrication of Plasma Nanotorch Tips for Localized Etching and Deposition

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***Abstract*—We present the microfabrication and initial testing of an AFM-tip like device, or nanotorch, that is capable of generating a very localized microplasma at its tip. The submicron region near its tip provides a unique manufacturing environment where new methods for controlled direct-write micro and nanofabrication can be tested. The device has been fabricated using both surface and bulk micromaching techniques. We demonstrated both localized submicrometer oxidazion patterning and imaging with the same device. Preliminary experiments have also been carried out demonstrating localized plasma etching of a polymer surface at atmospheric conditions with an AC voltage of 1000V.**

I. Introduction

The capability to realize automated, parallel fabrication of individual nanostructures with control over the position, size, shape and orientation of each structure at the nanometer scale is desired yet not possible at this time. One enabling approach to controlled micro and nanofabrication is the utilization of specialized direct-write AFM cantilevers and tips that can manipulate, etch and deposit features at sub-micrometer scale on the surface of a substrate.

Recently, several spot plasma tip techniques were developed. In [1-4] a tungsten carbide needle tube electrode with inner hole diameter of 150 µm; silica discharge tube with 0.7 mm diameter, line shape microplasma source with inner gas outlet dimension of 130 µm, and UHF inductively coupled quartz-glass discharge capillary of 100 µm inner diameter was used. These tips function as miniaturized version of plasma spray and cutting nozzles [5]. The minimum etched feature size achieved with these devices greatly depends on the size of the electrode and the gas inlet. With their electrode and gas outlet dimensions on the scale of 100 µm or larger, these techniques are only capable of sub-millimeter spot sizes lacking the resolution required for micro and nanofabrication.

In this paper we present a new type of AFM-tip like device, or nanotorch. This device consists of a sharp metal coated tip with integrated microchannels which deliver gases near the tip electrode. Such device is capable of forming a localized plasma, an energetic manufacturing environment that can produce reactive gas species for etching and deposition. The plasma is further localized under the effect of hydrodynamic focusing of incoming reactive gases.

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II. Nanotorch Device Concept

Fig. 1 shows a schematic of the nanotorch device. The device consists of two electrode leads, an apex tip and a microchannel. The entire structure is suspended on a silicon nitride cantilever. Electrical power is delivered to the tip using two electrode leads. The central electrode lead is buried within the microchannel leading to the tip apex. The second electrode lead runs on top of the microchannel forming a concentric ring around the apex. The microchannel is used to deliver processing gases to the apex. These gases can be plasma ignited by DC and AC signals. At the nanotorch apex, the device tip consists of an oxidation sharpened polysilicon tip coated with a thin layer of refractory Cr metal. The tip is protruding out of the interior of the microchannel through a small (~ 5µm) orifice. A strong refractory metal is necessary to (a) prevent erosion of the tip during the etching, and (b) plasma cleaning of any deposited material in a deposition mode. The substrate and cantilever are mounted on a conventional high resolution AFM micromanipulator stage that controls the displacement of the tip with < 5 nm positioning resolution. The back of the cantilever tip is coated with a thin reflective metal layer used to optically determine the vertical tip displacement.

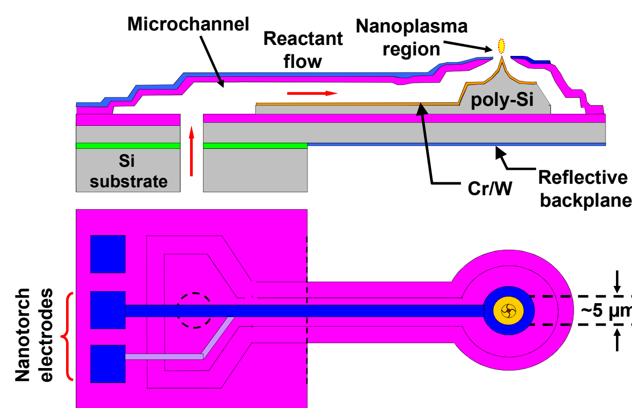

Figure 1. Simplified cross-section and top view of a plasma nanotroch tip. The device consists of a sharpened polysilicon tip that is coated with arefractory metal. The tip electrode is enclosed by a concentric silicon nitride wall microchannel that delivers reacting gases to the tip.

In order to ignite the nanotorch, first a flow of reactive or actived gases, such as Ar, SF_6, CHF_3 for etching and SiH_4 for deposition, for example, is introduced into the channel inlet. This flow exits the microchannel at the orifice. When a potential difference of a few dozen volts is established between the conductive microchannel walls and the tip, the very high electric field present at the sharp tip creates a highly confined plasma region where active species responsible for the etching and deposition are generated. These reactive species are transported upwards by the incoming flow toward a sample. Controlled localized etching and deposition could be accomplished through: (a) an active gas delivery system that ensures a continuous transfer of the new active species exiting the tip area, (b) highly localized electric fields near the tip and (c) hydrodynamic focusing that improve the plasma localization even further.

III. Device Fabrication

The nanotorch is fabricated as shown in Fig. 2. First a 2 µm layer of low-stress silicon nitride is deposited that provides structural support for the tip beam, and an opening is etched for the backside access hole. Next a 0.5 µm layer of oxide is thermally grown on the hole region. Next a 6 µm layer of doped low-stress polycrystalline silicon is deposited.

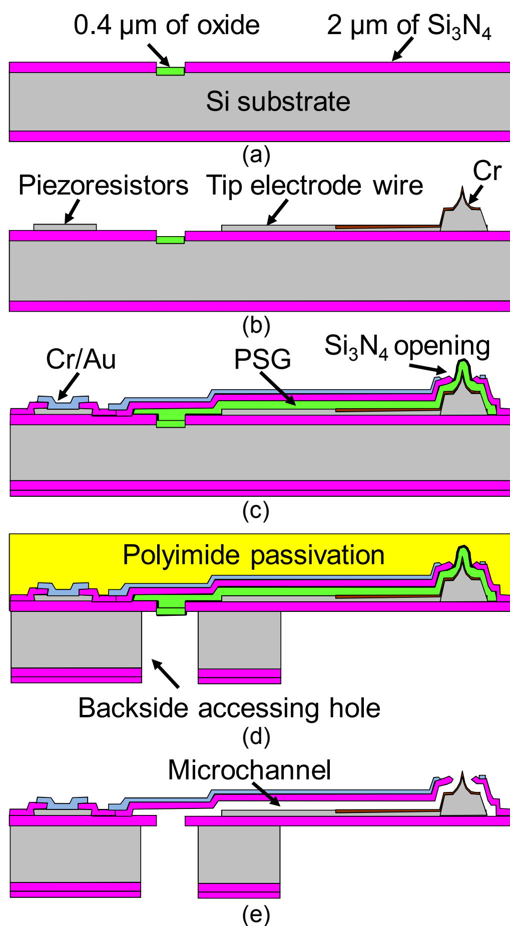

Figure 2. Simplified process flow of the plasma nanotorch device.

The polysilicon is patterned and time etched to form the tip apex leaving 1 µm on top of the Si_3N_4. A third lithography is defined, and the polysilicon piezoresistors and interconnect lines to the tip are defined down to the Si_3N_4. Next the tip is oxidation sharpened by growing 0.5 µm of wet thermal oxide. The oxide is next stripped. A layer of Cr is next sputtered on the wafer and patterned to metalize and harden the tip. Next we pattern a 0.8 µm of PSG sacrificial layer to from the microchannel. A 2 µm layer of low stress Si_3N_4 is deposited serving as the wall for the channel and piezoresistor passivation. Contact holes are opened for the piezoresistors and the tip. A layer of Cr/Au is sputtered and patterned to form the ring shape electrode leads. Next we open windows on the Si_3N_4 and etch down to the silicon with plasma etching. This step defines the shape of the released device. Before doing any backside processing, we first spin coat a thick (10 µm) layer of polyimide on top of the wafer which will keep the entire structure frozen in place while the backside material is released. Next we define openings on the wafer backside corresponding to the gas access hole leading to the microchannel and the beam regions. The wafer is next DRIE through the silicon wafer down to the oxide in the gas access hole region. This DRIE step also releases the cantilever beam. Device wafers are next half diced from the bottom and thoroughly cleaned followed by extended O_2 plasma that releases the entire structure. After separating the individual probe chips by mechanical cleavage of the half diced chips, the microchannel for each chip is finally released by sacrificially etching the PSG in HF. For the chips to be mounted to AFM micromanipulator stage, a layer of 0.1 µm Al is also deposited to the backside of cantilever beam to optically determine the vertical displacement. Fig. 3 shows several SEM photographs of the fabricated device.

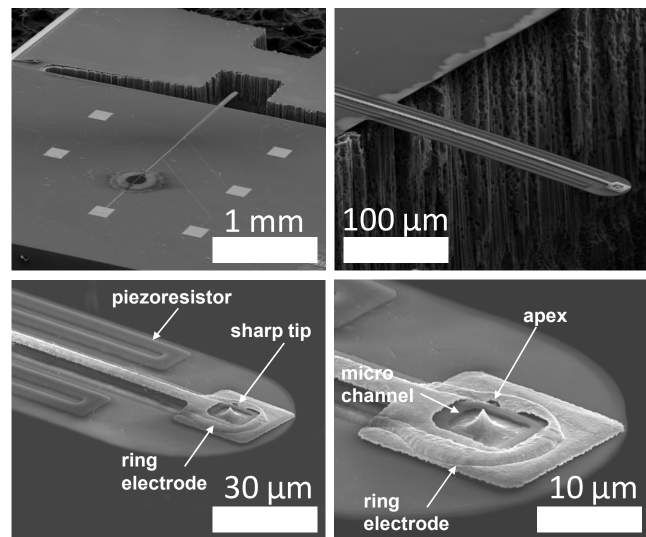

Figure 3. (top) SEMs of microfabricated nanotroch on a suspended cantilever beam 500 µm long . (bot) Close up SEMs of the nanotorch showing microchannel, apex tip and ting electrode.

IV. EXPERIMENT AND RESULTS

Imaging Test: The substrate and cantilever have been mounted to a conventional high-resolution AFM manipulator stage. This permits precise positioning of the tip related to the sample with a resolution less than 5 nm. The etch/deposition process and the imaging of the sample can be carried out using the same tip, which greatly reduces the difficulty of re-locating the etch/deposition spot during sample imaging. We have used our device to scan over several samples in contact mode (with our device's intrinsic frequency measured to be 67.8 KHz). Figure 4 shows two AFM images generated with our tip. The image on left is for a sample coated with gold lines. These lines are equally spaced and the thickness of the gold is about 100 nm. The image on the right is for a silicon sample partially coated with a layer of 15 nm Ti.

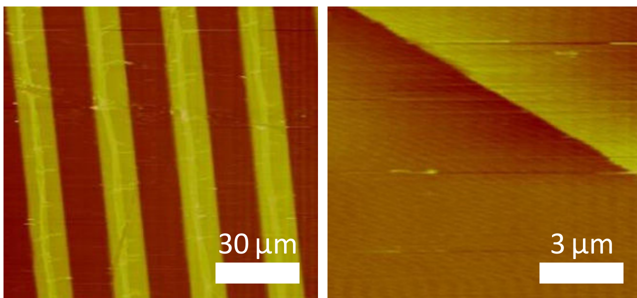

Figure 4. AFM images of two samples scanned with the nanotorch device.

Flow Tests: Experiments were carried out to test gas flow through the microchannel. The etching of the PSG sacrificial layer was first examined by cutting through the microchannel using FIB milling. Figure 5 shows a cross-section of a microchannel after the sacrificial etch. The actual thickness of the PSG sacrificial layer is about 0.9 µm, and the thickness of the Si_3N_4 cover wall is about 1.9 µm.

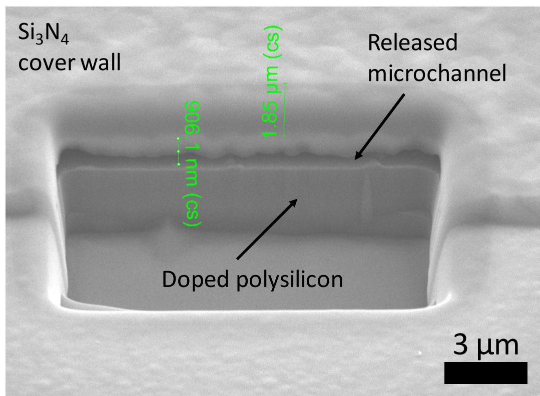

Figure 5. SEM photograph of the cross-section cutting through a realeased microchannel using FIB.

The device was next mounted to a substrate with connecting holes as shown in Fig. 6. The substrate material is PMMA and the connecting holes were created by drilling. After attaching the tubing to the substrate, the entire assembly was immersed into water and a compressed gas source of 20 PSI was used to force air through tubing and microchannel.

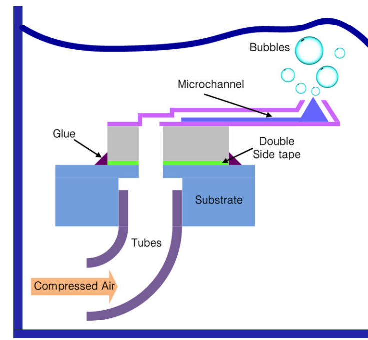

Figure 6. Experimental Setup to test the opening of the microchannel.

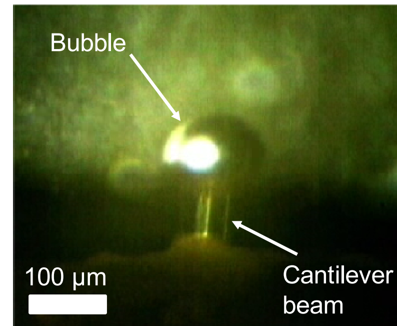

Figure 7. Photograph showing the bubble generated at the apex region when pressurlizing air through a device immersed in water.

Fig. 7 shows a photograph showing bubbles generated at the apex of the device indicating gas flow through the microchannel.

Localized Oxidation Tests: The oxidation of metal surfaces had been tested using our nanotorch device mounted on an AFM station under atmospheric conditions. Figure 8 shows the experimental setup. A doped silicon sample coated with a 10 nm layer of titanium was first taped to the AFM sample holder using double side tape.

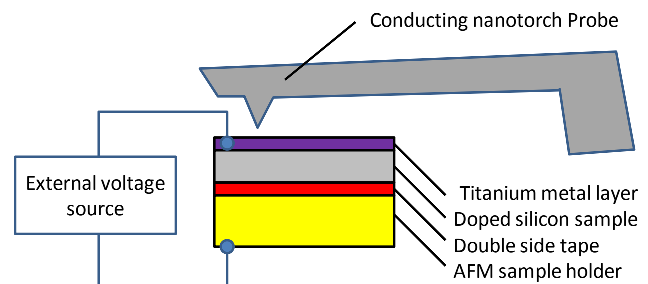

Figure 8. Experimental setup of the oxidation test.

After loading the sample and mounting the nanotorch probe, to oxidize the metal surface, a voltage of 20 V was applied between the titanium layer and AFM sample holder while with the tip connected to the ground. Under the control of the AFM software, the tip was slowly moved along a designed path during the oxidation. Next the oxidizing voltage was removed and the tip scanned and imaged the same region.

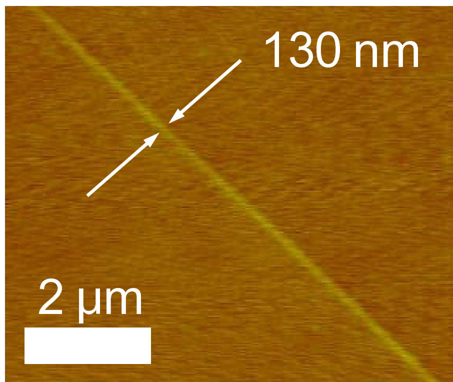

Figure 9. AFM image of an oxidized titanium line formed by the nanotorch device tip.

Figure 9 shows the image of the resulting titanium oxide line. The width of the line is about 130 nm. The oxide line width can be controlled by adjustment of both the applied voltage and the tip moving speed.

Plasma Tests: The device was next tested in an O_2 environment at atmospheric pressure using an AC voltage of 1000 V applied between the tip and ring shape electrode through the contact pads as shown in the setup of Fig. 10 (a). Fig. 10 (b) shows an optical image of the localized plasma near the tip. The plasma, as a source of electrons, ions, and radicals, can then be used for microscale and nanoscale fabrication.

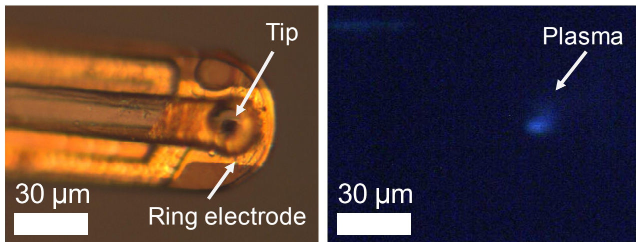

Figure 10. Optical photos of a microfabricated nanotorch device under test and the localized plasma generated at the device with 1000 V AC drive.

As a demonstration of the device capability for etching preliminary localized etching experiments at these conditions have been performed using the experimental setup shown in Fig. 11.

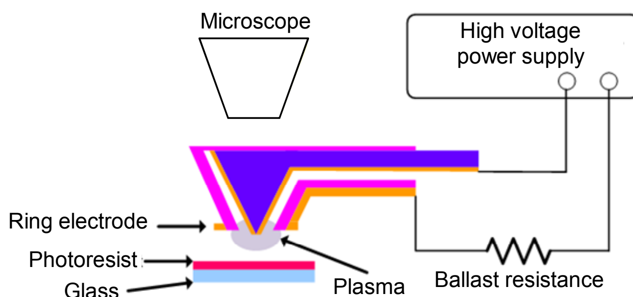

Figure 11. Experimental setup for localized photoresists experiment with the nanotorch device.

In the experiment, a glass slide coated with a thin layer of photoresist was etched. The high voltage AC source was applied to the device through a 1 MΩ ballast resistor. The ballast resistor was added to limit the AC power delivered to the tip. After connecting the power supply to the device, the assembly was placed under a microscope through which the etching process was observed and recorded from the opposing side of the slide. Figure 12 shows SEM and optical photographs of samples etched by the device. The left photo is a photoresist sample that was etched for a short time, and the right photo shows a sample that was etched for about 15 minutes. The plasma created a 6 µm diameter pit, about the size of the nozzle opening at the tip apex. Further experiments are needed to determine the experimental and environmental conditions (pressure, flow and bias) that can effectively focus and confine the microplasma to smaller dimensions.

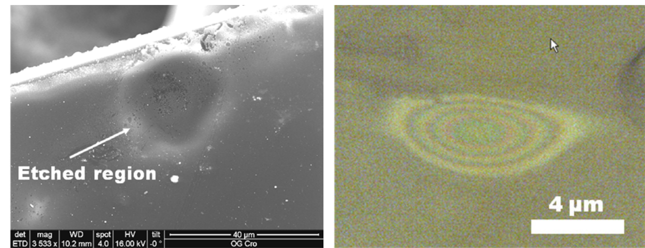

Figure 12. SEM and optical photos of photoresist sample etched by the nanotroch device under atmospheric conditions.

V. Conclusion

In this paper we present the microfabrication and initial testing of an AFM-tip-like nanotorch device. In this device, microchannels and electrodes are integrated with the AFM tip, enabling the generation of a localized microplasma around it. The microplasma region near the tip can provide a unique manufacturing environment where new methods for controlled nanofabrication can be tested. Several preliminary experiments have been performed to test the device capability for localized etching, oxidation and imaging.

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