

# Nanopatterning using NSOM probes integrated with high transmission nanoscale bowtie aperture

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**Abstract:** Nanoscale ridge aperture antennas have been shown to have high transmission efficiency and confined nanoscale radiation in the near field region compared with regularly-shaped apertures. The radiation enhancement is attributed to the fundamental electric-magnetic field propagating in the  $TE_{10}$  mode concentrated in the gap between the ridges. This paper reports experimental demonstration of field enhancement using such ridge antenna apertures in a bowtie shape for the manufacture of nanometer size structures using an NSOM (near field scanning optical microscopy) probe integrated with nanoscale bowtie aperture. Consistent lines with width of 59 nm and as small as 24 nm have been written on photoresist using such probes.

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**OCIS Codes:** (180.4243) Near-field microscopy; (220.3740) Lithography; (220.4241) Nanostructure fabrication.

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## 1. Introduction

Lithography is an essential tool in many areas, most importantly in the fields of manufacturing of micro and nanoelectronics, and like any tool, needs to be continuously upgraded to match pace with demand. Many novel processes, including near field photolithography [1,2], imprint lithography [3], and surface Plasmon-assisted nanolithography [4] have been devised to lower the feature size beyond the diffraction limit but one type of lithography stands out for its versatility. Probe lithography has lower cost and can be used with a wider variety of laser systems and substrates than traditional masked photolithography systems. It has been demonstrated both with an aperture [5] and without [6], which gives the system more flexibility to be tailored to the requirements of the user. Femtosecond lasers have also been used in conjunction with these lithography techniques to further reduce the resolution [7-9]. The high field intensity generated by these lasers can cause multiphoton absorption in the material which lowers the effective cross section of the exposure. One of the drawbacks to an aperture based system, like NSOM lithography with a nanoscale circular aperture, is the low transmission efficiency of energy onto the substrate [10]. Recent experiments have shown that ridge antenna or antenna apertures can both increase the transmission efficiency and decrease the spot size [11-14]. In this paper, we report experiments combining the NSOM and femtosecond laser approaches together with the use of ridge apertures for lithography applications.

## 2. Ridge aperture for field concentration and enhancement

Ridge apertures are a class of broadband apertures used frequently in microwave applications. One type of ridge aperture has a bowtie shape, which is called bowtie aperture. As shown in Fig. 1, the bowtie aperture consists of two open arms and a small gap formed by two sharp tips pointing to each other milled through a metal screen. It has been shown recently that light at optical frequency can pass through the ridge aperture without experiencing much intensity decay [15-17]. The transmitted light is confined to the nanoscale gap region offering an optical resolution far beyond the diffraction limit. The sharp tips further enhance the local electric field via either lightning rod effect or resonant excitation of localized surface Plasmon [18].

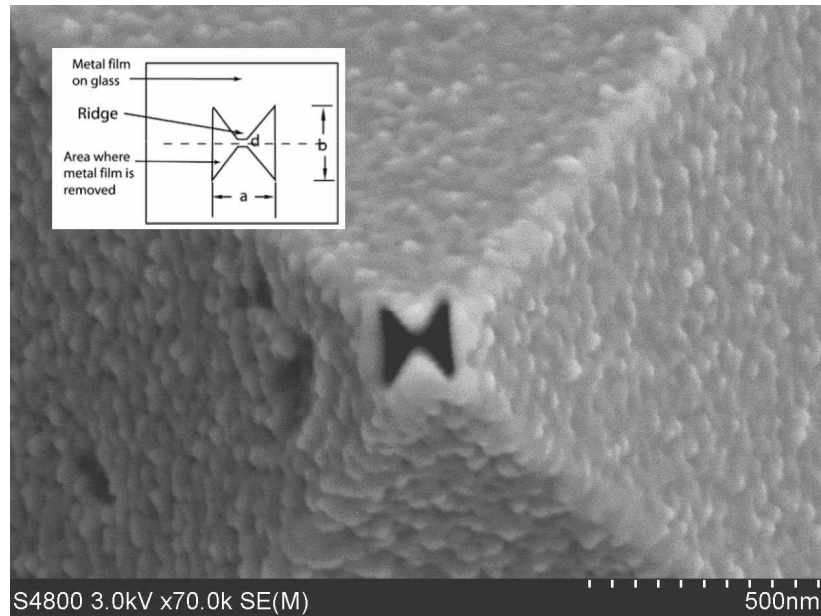


Fig. 1. SEM image of a bowtie aperture on AFM probe with inset of idealized geometry.

In this work, bowtie apertures were specifically designed for nanolithography at the 800 nm Ti:sapphire femtosecond laser wavelength using finite difference time domain (FDTD) numerical simulations [17]. A small gap is desirable because the light spatial concentration is determined by the gap size. However, since the bowtie aperture was fabricated by focus ion beam (FIB) milling technique, the smallest gap size that can be practically fabricated using our FIB system is about 30 nm due to the limitations of both finite ion beam size. Thin aluminum film was selected as the bowtie aperture material because of its small skin depth and high reflectivity. The thickness of aluminum film was chosen to be 120 nm, which not only is sufficiently thick enough to completely block transmitted light directly through the film but more importantly eliminates the light leakage from the bowtie arms caused by the aperture end effect. With all these conditions and parameters in mind, the bowtie aperture was designed to be able to achieve a sub-50 nm near-field light spot with unity transmission efficiency at 800 nm normal illumination.

The bowtie aperture probe as shown in Fig. 1 is made by modifying a standard silicon nitride AFM probe. A layer of aluminum 120 nm thick is evaporated onto the tip side of the cantilever. FIB milling is used to produce the aperture. The outline dimension of the aperture is about 160 nm.

### 3. Experimental setup

Laser light of 800 nm wavelength and pulse width of 50 fs produced by a Ti:sapphire oscillator pumped by a solid state laser was utilized in the experiments. A cube polarizer was used to attenuate the vertically polarized light from the oscillator and a half wave plate to reorient the polarization across the bowtie aperture gap, as required for achieving high transmission through the ridge aperture [17]. A beam splitter redirected the laser light to the 50X objective lens as well as permitting monitoring via a CCD camera. A home-built NSOM head was designed and constructed with a set of motors that moved the entire head to bring the probe into contact with the sample surface. A separate piezoelectric stage handled both X and Y movements as well as the height adjustment during scanning. A filter for 800 nm light was included on the feedback laser path to protect the position sensor from damage from the high energy laser pulses. A diagram of the setup is shown in Fig. 2.

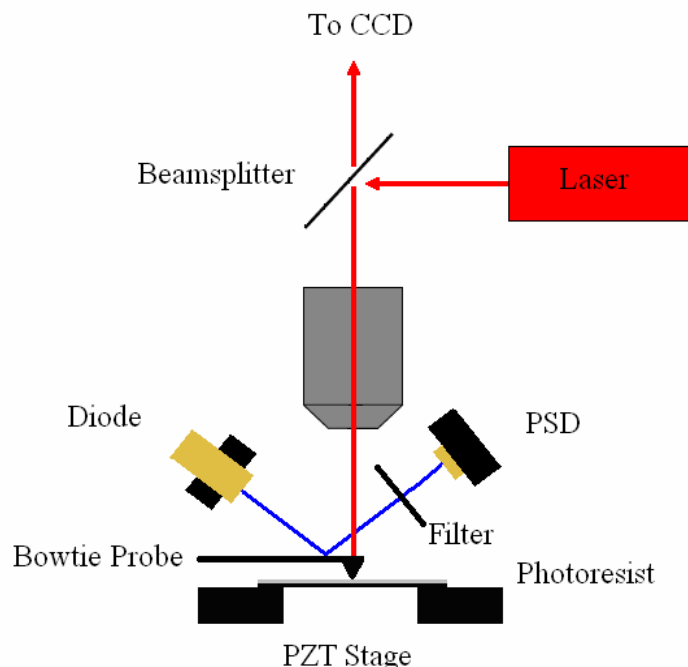


Fig. 2. Schematic diagram of the NSOM lithography setup.

Shipley S1805 positive photoresist with sensitivity at 436 nm was spun on a glass surface at 5000 rpm giving a thickness of 400 nm. Soft baking at 95 deg C for one and a half minutes was followed by the exposure. Development was performed using a standard mix of 351 developer and DI water with a 1:3 ratio for 10 seconds. Since the 800 nm wavelength from the fs laser is longer than the sensitive wavelengths of the photoresist, a two-photon process is expected for photoresist exposure.

#### 4. Results and discussion

The bowtie aperture probe was used in the NSOM system to produce line patterns while scanning speeds and incident powers were varied. Probes with 300 x 300 nm and 100 x 100 nm square apertures were also fabricated and tested to give a comparison for lines drawn by the bowtie aperture probe. A summary of the test results is shown below in Table 1.

Table 1: Summary of testing results for the three probes showing linewidth in nm. Surface power is the power on the cantilever surface, same for both speeds for each antenna.

Speed	300 nm probe	100 nm probe	Bowtie probe
2.5 $\mu\text{m}/\text{sec}$	286	92	72
5.0 $\mu\text{m}/\text{sec}$	177	No result	59
Surface power (mW)	7.9	2.5	1.5

The 300 and 100 nm aperture probes were expected to produce linewidths of approximately the same size as the apertures themselves. The test data show that the regular apertures produced the expected results at slow scan speed (2.5  $\mu\text{m}/\text{sec}$ ). On the other hand, the smaller linewidth (177 nm) produced by the 300 nm aperture at high scan speed was a result of using a combination of dose and laser power very near the threshold, similar to

achieving a sub-diffraction limit spot using the peak of a Gaussian laser beam in laser micromachining. No results were available for the 100 nm probe at the higher speed due to the below threshold exposure dose.

The bowtie aperture test results show line widths were smaller than the overall dimensions of the aperture (160 nm), illustrating the light confinement properties of the ridge aperture. The bowtie probe produced a linewidth as small as 59 nm at a higher scan speed. An AFM image of the smallest line obtained with the bowtie probe is shown in Fig. 3. Further lowering the energy dose by increasing the scan speed or decreasing the laser power can generate a narrower linewidth, but with a loss in repeatability.

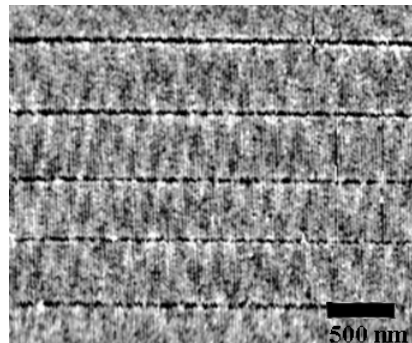


Fig. 3. AFM scan of bowtie lines with cross section view.

An interesting discovery during our experiments is that the lithography results exhibited a dependence on the scanning direction resulting from the probe and surface interactions. Fabricating the aperture on the tip using FIB creates a relatively flat region right at the tip, and the cantilever bends differently in response to different scan directions. These result in variations in the aperture and surface spacing which change the exposure intensity of the photoresist and therefore the linewidth. This is most apparent during circular motions where the scan direction is constantly changing, as seen in Fig. 4 with a constant surface power of 1.5 mW and scan speed of 5.0  $\mu\text{m}/\text{sec}$ , where the width changes continuously with the widest portions at the top and bottom and the narrowest near  $\sim 45^\circ$  from the top and bottom direction where it is only 24 nm wide. The line quality of the circle decreases as it approaches the near vertical sections and becomes indistinct at the sides under SEM imaging. These results of the linewidth changes in a circle are repeatable. The reasons for obtaining a narrow linewidth can again be a result of the near threshold dose same as seen in the result of 177 nm lines produced by a 300 nm square probe (Table 1).

At this time, there is no active control in our system to adjust the bending angle of the cantilever during scan. Current work on implementing better control of the bending angle as well as using the non-contact mode is being carried out in order to achieve small linewidth and eliminate the dependence of the linewidth on scan direction.

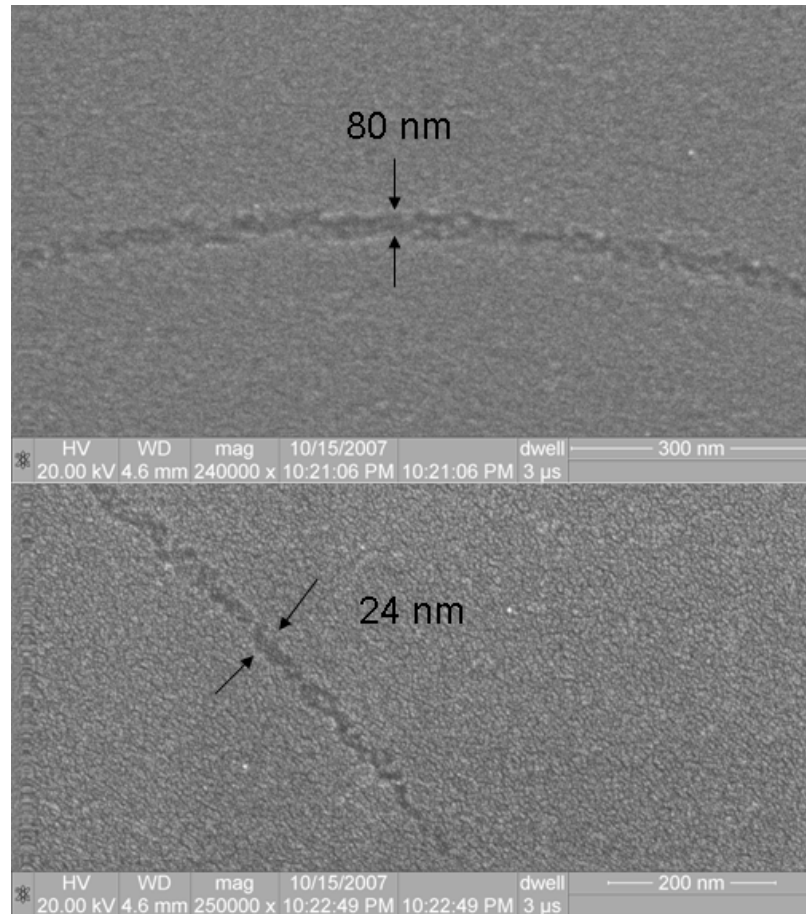


Fig. 4. SEM of circle pattern showing top and side sections of a circle.

## 5. Conclusion

In summary, it was shown that the combination of probe lithography, two-photon lithography, and nanoscale bowtie apertures was able to successfully manufacture nanoscale lines beyond what was expected with a regular aperture. The advantages of bowtie aperture for nanolithography were demonstrated by performing near-field photolithography experiments using an NSOM probe integrated with a bowtie aperture. Isolated line segments as narrow as 24 nm linewidth were produced on a positive photoresist coated sample. The lithography results clearly show bowtie aperture has much better performance over regular apertures probes.

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