Nano-structuring with laser illuminated scanning probe tip array

David Jen Hwang, Anant Chimmalgi
Department of Mechanical Engineering UC Berkeley

Abstract

Nano-structuring of various materials is important for a number of future oriented technical applications. Local intensity enhancement of laser irradiation in the near field of a SPM tip enables the processing of sub-diffraction limit features. The tip-sample gap, which is a critical parameter for the field enhancement needs to be very precisely controlled. In the present work, the design of lateral motion comb drive for the sub-nanometer precision gap control is focused. The practical implementation of such a nanostructuring system can be realized only by utilizing one-dimensional array structures of tips simultaneously operating in their respective cells. The nano-positioning device with its sub-nanometer resolution proves to be an efficient tool for the precise control of the enhanced field and hence of the feature produced.

Introduction

Nanostructuring of a variety of materials has gained enormous importance in the recent times due to its numerous applications in the fields of ultra-high density information storage, mask production and repair in the semiconductor industry, biotechnology etc. [1] Due to the improved speed, accuracy, precision and finish, laser based material structuring is being explored for applications in a variety of areas. Use of ultra short pulse laser has been proved to be an extremely powerful tool for micromachining. Both the influence of heat conduction through the material and screening of the incident beam by vapor/plume in case of longer pulse have been observed to be strongly diminished [2]. However, the spatial resolution using far field optics is restricted by the diffraction limit of the beam. Operating near the sharp ablation threshold in ultra-short pulse makes it possible to machine under the diffraction limit but the feature size is affected very sensitively by the fluctuation of laser power [3]. In order to overcome this diffraction limit drawback, electron beam or X-ray modification can be utilized. However, these fail to fulfill the requirements of high throughput, the registration for mass production tool and flexibility in three-dimensional machining [4]. Thermo-mechanical writing using arrays of AFM tip, has been shown to produce sub-diffraction limit features. But residual stresses introduced by the tip and non-repeatability of the features due to the wear of the tip seriously limit the usage of this technology for reliable modification of materials [5].

Use of near field by scanning probe microscopy (SPM) such as scanning near-field optical microscopy (SNOM), scanning tunneling microscopy (STM) and atomic force microscopy (AFM) in combination with laser light, is a possible solution which permits high spatial resolution surface modification and possible integration to achieve the goals of mass production [2]. Instances of use of μ−STM arrays operating in parallel for nanolithography are available in the literature [4], but even with this method serious limitations are placed on the conductivity of material being processed requiring it to be a good electric conductor thus making it unsuitable for biotechnology applications on organic specimens.

In this paper the authors propose a nanomodification scheme utilizing ultrashort pulse laser irradiation in the near field of a single-dimensional SPM-tip array. Using the array scheme, in addition to high-throughput and versatility in the choice of the substrate material, an effective solution to a variety of selective modification processes like nanolithography, nanostructuring by material ablation and nanodeposition to name a few, is provided. The present work discusses the theoretical and fabrication aspects of nanostructuring using the proposed scheme. Highly accurate tip positioning using a lateral comb-drive unit, in order to maintain a constant tip-sample surface separation and retract the tip selectively, is also proposed. In addition, the simulation results for the optimal design of the same are provided.

Theoretical considerations of the Near-Field of a SPM-Tip

The use of field enhancement of optical radiation in the near field derives its origin from Surface Enhanced Raman Scattering (SERS) [6]. Amplification of an electromagnetic field incident on metallic particles is due to phenomena of “lightning-rod effect”, localized tip induced surface plasmons and by propagating surface plasmons [6,7]. For incident infrared light the tip-end behaves like a *long-wire antenna* as the tip is thinner than the wavelength whereas in case of visible radiation the tip is not sharp enough to serve as a thin antenna and so the field enhancement is mainly due to the tip-induced plasmons and propagating surface plasmons [7].

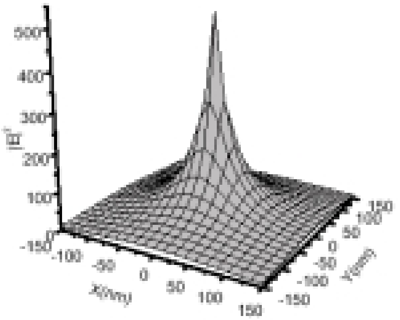


Fig.1. The electric intensity distribution over a gold surface underneath a silver SPM tip[8]

The intensity distribution underneath a tip irradiated by a laser which is p-polarized and incident parallel to the sample surface, behaves as shown in Fig.1 [8]. It can be clearly observed that an enhancement of around 500X is obtained. Also the distribution changes very sharply and considering 1/e of the maximum intensity level we can infer that the spot size is approximately 60nm. Thus not only are we able to enhance the intensity by sufficient amount but also we are successful in producing features in the sub-diffraction limit.

Tip array design and fabrication

SPM tip array consists of cells each of which contains sets of tip, lateral comb actuator, springs, and necessary wiring as shown in Fig.2. Here, we primarily concentrate on the optimal design of comb actuators and springs. The force between the tip and sample is estimated to be typically of the order of 10^{-7} N [9], and hence the actuator should overcome this attraction force, which in our design, corresponds to 13 nm of deformation. It has been reported that the tip height inhomogeneity is order of ±50 nm. To overcome this, we propose to operate in two steps – Tip calibration, and actual modification process. In the first step, we align the tips using a conducting sample as a reference (e.g. Gold Palladium layer deposited on Mica with RMS surface roughness of the order of less than 0.3 nm [10]) by monitoring the tunneling current of each tip [11]. Thus, the required maximum deformation of the most erroneous tip is 113 nm and hence comb actuator is designed to cover this range. Once the tips are aligned, the external XYZ piezo scanner further precisely controls the sample-tip gap. For regions where modification is not needed, proper switching retracts the tips far enough, so that two voltage sources are connected serially and field enhancement no longer exists.

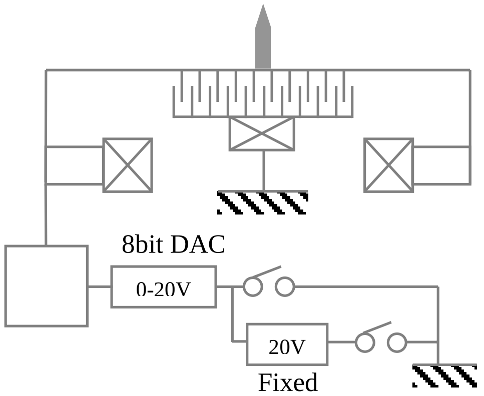


Fig.2. Unit cell of the SPM array.

The experimental setup consists of a piezo XYZ scanner with sample holder, SPM-Tip array mounted in a suitable holder, and optics for the alignment of laser beam as shown in Fig.3. Femtosecond laser pulses from a Ti-Sapphire laser is focused at grazing incidence angles on to the surface to avoid direct laser induced damage to the sample and the tip array. Laser intensity of the order of tens of MW/cm^2 is applied.

Fabrication of the tip array is done using SOI wafer. For sharpening the tip, focused ion beam milling is used. Process flow is as follows :

(a) Start with SOI <100> wafer
(b) DRIE for trench
(c) Backfill and deposition with oxide for the protection of upper silicon
(d) Backside KOH etching for tip exposure
(e) Etch away sacrificial oxide layer for releasing the structures
(f) Focused ion beam milling for tip sharpening

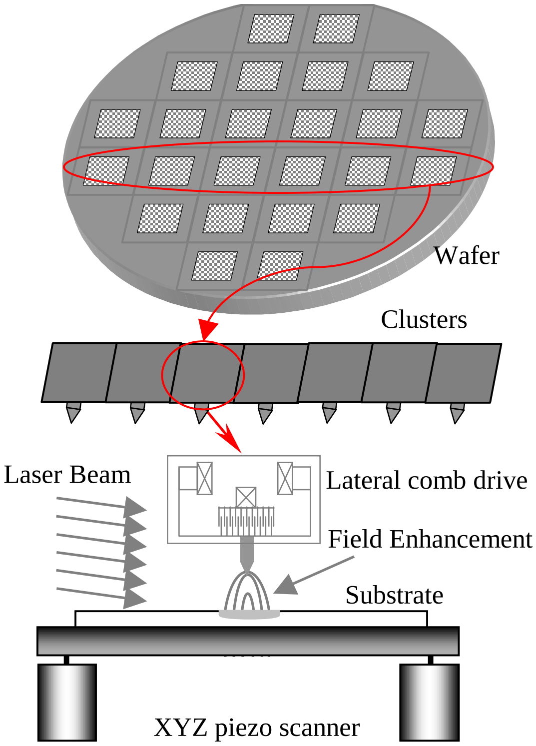


Fig.3. Nanostructuring setup with the SPM tip array

Results and Discussion

For the purpose of design analysis, deformation is estimated by SUGAR code with beam structure shown in Fig. 4. Electrostatic forces on the comb are replaced by a distriuted load on the beam, and the tip-sample attraction force by a concentrated force of 10^{-7} N. Several optimization cycles using the objectives of minimum cell size and required tip deformation, resulted in 160×55 μm^2 of structure area with ten comb finger. 2μm feature size for the comb structure, 10μm widths for the anchor and 60μm structure thickness , are assumed.

Fig. 5(a) shows the behavior of tip deformation by varying the applied voltage. For a voltage less than 20 V, an almost linear behavior is observed, and this is the range in which we wish to operate for the tip alignment. 6 nm/V of average control resolution is possible in this region, and if further an 8-bit DAC control is applied, the resolution improves to less than 0.5 nm. Operating in higher voltage range, though results in higher deformation, but leads to significant degradation of the resolution (e.g. for near 40V range with 8-bit DAC control, the resolution is of the order of 3.2 nm.). Fig. 5(b) shows the dependence of the resolution near the applied voltage using 20V maximum voltage source and 8-bit DAC. By serially connecting the two voltage sources shown in Fig.2., the tip is retracted by several hundreds of nanometers. This eliminates any surface modification as intensity enhancement no longer occurs.

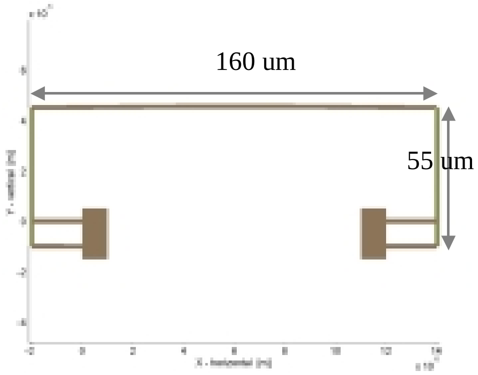
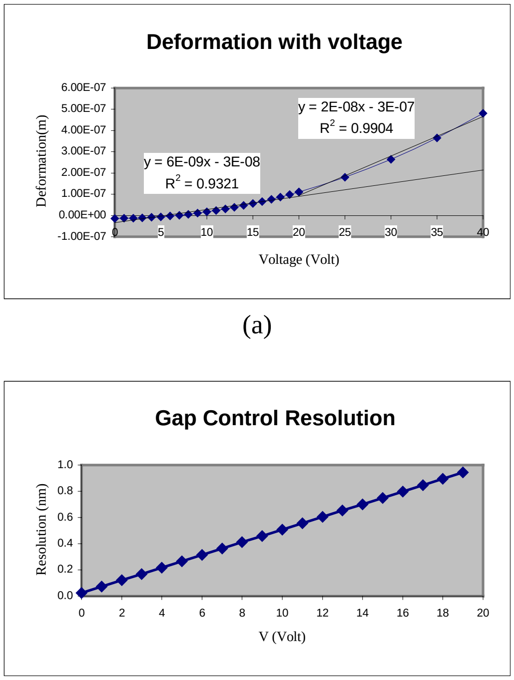


Fig.4. Design analysis by SUGAR

The need for such a high resolution can be seen from Fig.6. which shows the variation of enhanced field intensity with the tip-sample gap. With high gap control resolution obtained above, we can precisely control the enhancement effect [12].

Conclusion

To overcome the diffraction limit of far field optics, structuring by use of near field of SPM tip coupled with femtosecond laser was proposed. For higher throughput of processing, one-dimensional array scheme was applied and high resolution nano-positioning device using comb drive actuator was designed. The nano-positioning device with its sub-nanometer resolution proved to be an efficient tool for the precise control of the enhanced field and hence of the feature produced.



(a)

(b)

Fig.5 (a) Calculated behavior of tip deformation with the applied voltage. (b) Resolution near the applied voltage using 20V maximum voltage source and 8-bit DAC.

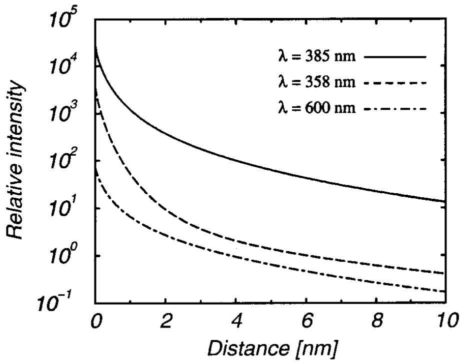


Fig. 6. Variation of enhanced field intensity with the tip-sample gap [12]

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