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LASER LITHOGRAPHY BY PHOTON SCANNING TUNNELING MICROSCOPY

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ABSTRACT

We have investigated the possibility of using a photon scanning tunneling microscope (PSTM) for laser lithography. A contrast enhancement material (CEM) is coated onto a sample slide and coupled to the prism of a PSTM. The CEM becomes transparent above a laser (HeCd at a wavelength of 442 nm) intensity threshold attained due to the proximity of the probe tip. The same surface can then be inspected using the given experimental configuration by replacing the HeCd laser line with a non-exposing 633-nm HeNe laser line. Direct patterns can be produced by varying the exposure time and the shape of the probe tip.

INTRODUCTION

Since the early 1970s, developments in optical lithography have shrunk linewidth-patterning capabilities from 7 μm to below 1 μm . Restricted by the diffraction limits, the best linewidth can be obtained at approximately $\lambda/2$ where λ is the wavelength. The resolution of an optical microscope is also restricted by the far-field diffraction limit since the lens is many wavelengths from the sample. However, that is not a fundamental limit of optics. Scientists have overcome the diffraction barrier for optical microscopy by using a local probe in the photon scanning tunneling microscope (PSTM)¹ and the near-field scanning optical microscope (NSOM).^{2, 3} The basis of operation of the PSTM lies in the sample modulated tunneling of internally reflected photons to a sharpened optical fiber probe tip. In this experiment, we apply the PSTM principle to produce the laser lithograph on a submicrometer scale.

APPARATUS AND EXPERIMENTAL METHOD

A schematic of the PSTM is presented in Figure 1. An incident laser beam passes into a quartz prism (refractive index: 1.46) at an angle of 55° so as to exceed the critical angle at the base. It is thus reflected internally (i.e. total internal reflection) at the base of the prism. The evanescent field produced by the total internal reflection and extending out of the base of the prism is the source of the tunneling photons. A sample slide can also be optically coupled to the prism to provide an extension of the prism surface. When a fiber optic tip approaches the sample, the photons inside the sample are able to tunnel through the gap and are collected by the fiber. The tunneling photons are detected, digitized, and recorded by a photomultiplier

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Fig. 1. Schematic diagram of the apparatus.

Fig. 2. Image width as a function of exposure time.

and displayed as an image by a computer. The PSTM scan head has a fiber tip mounted on a piezoelectric tube. Potentials up to a few hundred volts are applied to the tube to provide precise motion in three-dimensions. The scanning motion is controlled by feedback electronics, as shown in Figure 1. The feedback circuit maintains a constant photo current by adjusting the vertical position of the tip while tracing along the sample surface. Each vertical position with the corresponding lateral position is recorded by the computer, so at the end of the scan a three-dimensional image can be formed on the monitor. All the scanning parameters, such as size, speed, and level of photocurrent, can be adjusted and entered by the computer. The position of the fiber tip can also be adjusted by a manual-control unit. The images can be saved in the hard disk of the computer for future analysis.

The contrast enhancement material (CEM) is a photosensitive composition that is commercially available (MicroSi, Inc.). It was spin-coated onto a quartz slide to a thickness of approximately 600 nm in accordance with the parameters given by the manufacturer. The sample slide was optically coupled to the prism and then exposed using a 442-nm HeCd laser line. The CEM was initially opaque (transmission: 4.0% max.) to the imaging light, but became nearly transparent (transmission: 90% min.) after the exposure due to its photobleachable characteristic. The refractive index at wavelength 480 nm is 1.66. Since the 633-nm HeNe laser line is not in the absorption region of the CEM, it was used for PSTM illumination in examining the result after the exposure.

RESULTS AND DISCUSSIONS

The effect of background exposure (i.e., the total-internal-reflection causes bleaching from the back of the CEM film) from a HeCd laser on the CEM is determined by measuring the exposure time without the photon tunneling (i.e. the fiber probe is kept away from the surface). At 4 mW, the exposure time required to bleach the CEM was 6 minutes. For lithographic exposure the tip was positioned 200 nm above the sample for various times. The exposure was evaluated by switching to a HeNe laser for three-dimensional image-scanning. An image of a tip was obtained with good contrast in 30 seconds. Extended exposure produces a slight widening effect in the first three minutes, as shown in Figure 2. After three minutes, the image width remains constant. A line scan was made across the image to measure the difference of the photocurrent between the image and the background (which we defined as contrast in Figure 2). Due to the background exposure, the contrast gradually degraded, as shown in Figure 3. The best contrast could be obtained between 30 seconds and 1 minute. In Figure 4, a simple local exposure of one minute showed the tip's shape best. The picture suggests that lithography linewidths of 100 nm or better could be obtained. At two minutes, the details of the image were degraded and the image-width widened (Fig. 5). Figure 6 shows a scanning electron micrograph of the fiber tip used in these exposures. Note that the small

Fig. 3. Image contrast as a function of exposure time.

Fig. 4. The tip image at one-minute exposure time. Scan size is $1\text{ }\mu\text{m} \times 1\text{ }\mu\text{m}$. The light area shows an increase in photocurrent.

Fig. 5. The tip image after a two-minute exposure time.

Fig. 6. The SEM picture of the tip used to produce the exposures in Figs. 4 and 5.

groove in the top of the tip is illustrated as the dark spot in the exposure shown in Figure 4. The presence of a tip with submicron structures enhances the bleaching effect, and the strength of the enhancement depends on the distance between the CEM and a particular structural feature. Due to the exponential nature of the evanescent field the exposure occurs only for such nearby structures. This enhancement may be due to photon reflection from the probe tip surface while photons are tunneling. Further study is needed to confirm our conclusion. This mechanism could be used to advantage in three-dimensional lithography.

We have shown that PSTM can be used as a laser lithography tool at submicrometer resolution. As with all other types of lithography, a well selected exposure provides a good image. It should be possible to replace the CEM by photoresist and obtain the same result. Tip control software could also be used to perform direct-write lithography with arbitrary patterns.

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