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Optical near-field lithography on hydrogen-passivated silicon surfaces

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We report on a novel lithography technique for patterning of hydrogen-passivated amorphous silicon surfaces. A reflection mode scanning near-field optical microscope with uncoated fiber probes has been used to locally oxidize a thin amorphous silicon layer. Lines of 110 nm in width, induced by the optical near field, were observed after etching in potassium hydroxide. The uncoated fibers can also induce oxidation without light exposure, in a manner similar to an atomic force microscope, and linewidths of 50 nm have been achieved this way. © 1996 American Institute of Physics. [S0003-6951(96)03730-8]

Over the last decade, the scanning near-field optical microscope (SNOM)¹ has become a very popular tool for optical imaging, photoluminescence spectroscopy, and surface modifications in the submicrometer regime.²⁻⁶ The SNOM is a direct spin off of the invention of the scanning tunneling microscope (STM) and the atomic force microscope (AFM).^{7,8} In contrast to conventional optical microscopy the interaction with the sample in a SNOM is based on the nonpropagating, or evanescent field mode, so that the achievable lateral resolution surpasses the far-field diffraction limit. In recent works by Mlynek *et al.*⁵ and Smolyaninov *et al.*,⁶ the technique of using a SNOM for direct writing in photoresist has been reported. Lateral resolutions of 80 and 100 nm have been demonstrated using metal-coated probes and uncoated probes, respectively. Another very promising lithographic process is patterning of hydrogen-passivated silicon surfaces via local oxidation. This technique has been introduced using STM,⁹⁻¹³ AFM,^{14,15} and electron beam lithography.^{12,16} Kramer *et al.*¹⁷ have recently reported on a purely optically induced oxidation. An optical interference pattern ($\lambda=350.7$ nm) has been projected onto a hydrogen-passivated silicon surface, which produces submicrometer lines after etching.

In this letter, we report on a novel lithographic technique, where a reflection SNOM has been used for local oxidation of a layered silicon structure. A passivated amorphous silicon surface was locally illuminated through an uncoated tapered fiber probe. The 457.9 nm line from an argon ion laser was used as the illumination wavelength. This wavelength matches approximately the Si-H binding energy of ~ 3 eV.¹⁷ Directly written optically induced lines down to 110 nm in width have been measured after exposure and potassium hydroxide (KOH) etch. Further, linewidths of 50 nm have been observed without light exposure, probably produced by an electrostatic potential between the fiber probe and the amorphous silicon layer.

A schematic diagram of the SNOM setup is shown in Fig. 1.¹⁸ The most important single component is the SNOM probe, an uncoated tapered single-mode optical fiber. The probe-to-sample distance is controlled by a shear-force

microscope.¹⁹ For general purposes, this enables simultaneous imaging of topographical and optical features with subwavelength resolution. SNOM probes are drawn from standard single-mode optical fibers in a commercially available micropipette puller.²⁰ A scanning electron microscope is used to characterize the size of the probes. The radius of curvature of the very end of the probes is typically 10–15 nm. Compared to the more commonly used metal-coated fiber probe,²¹ the uncoated probe has some important advantages. In terms of manufacturing, the reproducibility is higher since the coating process is avoided. This also reduces the fabrication time. In terms of instrumentation of the SNOM, the uncoated probe is more convenient to work with since it provides a more efficient coupling to the evanescent field mode. Further, heating and melting problems of the metal coating are completely avoided.

Samples for the writing process are prepared by growing a 1000 Å thick thermal oxide on a Si(100) substrate. A hydrogenated boron-doped amorphous silicon layer with a thickness of 135 Å is then deposited onto the thermal oxide by dc magnetron sputtering. The samples are dipped in 5% diluted hydrofluoric acid (HF) for 60 s to passivate the sur-

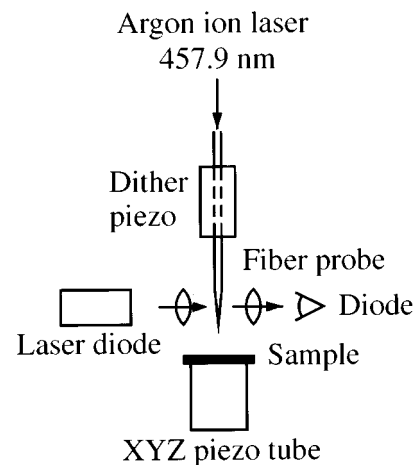


FIG. 1. Schematic of the reflection mode SNOM setup. The SNOM probe is an uncoated tapered single-mode optical fiber. The illumination source is an argon ion laser operating at $\lambda=457.9$ nm. The SNOM employs a shear-force microscope to control the probe-to-sample distance.

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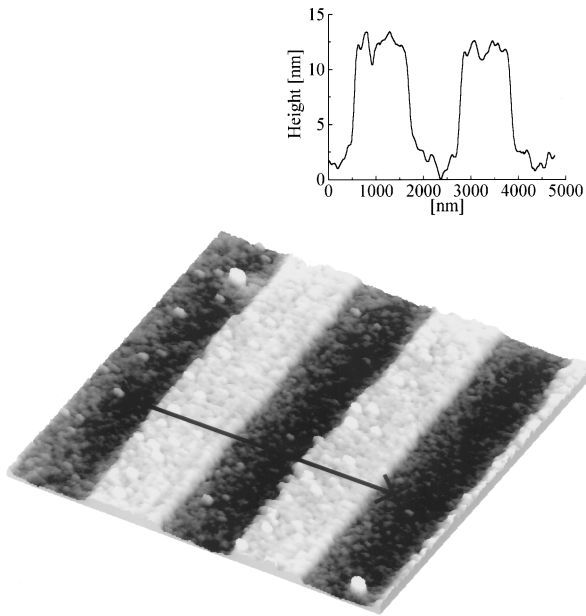


FIG. 2. AFM image ($5.7 \times 5.7 \mu\text{m}^2$) of optically induced double lines in a hydrogen-passivated silicon surface. After exposure the sample is etched in KOH. The period of the line grating is $2.2 \mu\text{m}$. The image is taken in contact mode.

face with hydrogen. The passivated surfaces are stable for at least 4 h after the HF dip.

Using the SNOM, a line grating pattern with a period of $2.2 \mu\text{m}$ is written via local desorption of hydrogen in air at room temperature. This causes a local oxidation of the silicon surface where the hydrogen passivation is removed. Different writing intensities, probe shapes, and scanning speeds have been investigated during the experiments. The locally grown native oxide is, then, used as a wet etch mask. The samples are etched in KOH for 30 s at room temperature, and characterized in a Rastroscope 4000 AFM, operating in contact mode. During the direct writing process, the laser output power is stabilized at 120 mW. The maximum far-field intensity emitted from a typical SNOM probe is measured to be $\sim 25 \text{ mW}$. With a scanning speed of $80 \mu\text{m/s}$, and assuming an exposed area of $1 \mu\text{m}^2$, the maximum achievable illumination dose reaches $\sim 30\,000 \text{ J/cm}^2$, which is sufficient for hydrogen desorption.¹⁷

Figure 2 shows an AFM image of a line pattern written with the SNOM after the KOH etch. The inserted cross-sectional profile clearly illustrates the $2.2 \mu\text{m}$ period of the pattern, and the height of the pattern transferred into the amorphous silicon layer after the KOH etch is about 10 nm. To determine the linewidth, the scanning algorithm must be known. The exposed area consists of 32 parallel lines separated by $2.2 \mu\text{m}$. After scanning one line in the forward direction, the probe should ideally return along the same line to its initial position. However, due to creep in the piezoelectric scanner tube, the lateral position of the probe is displaced when returning to the starting point. Since the SNOM is active during both forward and backward scans, this leads to a broadening of the exposed area in Fig. 2 due to an overlap of two slightly displaced scans.

In some regions, the creep effect is large enough to separate forward and backward scans. Such an area is shown in

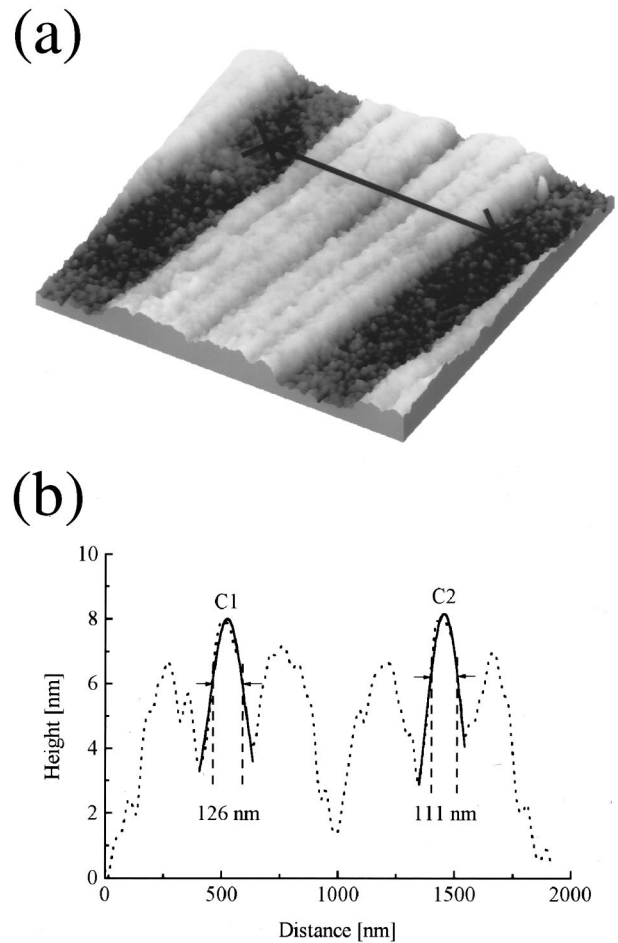


FIG. 3. (a) AFM image ($3.5 \times 3.5 \mu\text{m}^2$) of two separate scans. The narrow center lines are believed to be directly written with the optical near field. The broader side lines are introduced via an interference pattern, mainly dominated by the optical far field emitted from the side walls of the uncoated fiber probe. (b): Cross-sectional profile of (a). The widths of the center lines, C1 and C2, are 126 and 111 nm, respectively. The widths of the side lines are typically 200–230 nm.

Fig. 3. Three lines are observed in each scanning direction, a narrow center line and two slightly broader side lines. A cross-sectional profile of Fig. 3(a) is seen in Fig. 3(b). The narrow center lines, labeled C1 and C2, are believed to be directly written with the optical near field emitted from the very end of the fiber probe. The side lines are interpreted to be the result of an interference pattern, mainly dominated by the optical far field emitted through the side walls of the uncoated probe. The spacing of the side lines from the center line is 230–240 nm, i.e., approximately $\lambda/2$. A similar pattern has recently been observed in connection with near-field lithography on photoresist, also using uncoated fiber probes.²² Theoretically, the same kind of intensity distribution has been predicted by Bozhevolnyi *et al.* in relation to phase conjugation of optical near fields.²³ It should be noted, that the radius of curvature of the probes, as measured with a scanning electron microscope, is at most 20 nm. After scanning, the probes were checked to confirm their shape had not changed. Thus, the side lines cannot be due to a multiple tip effect. The experimental data representing the shape of the center lines are best fitted by a Gaussian intensity distribution (solid line). The widths of the center lines are in the

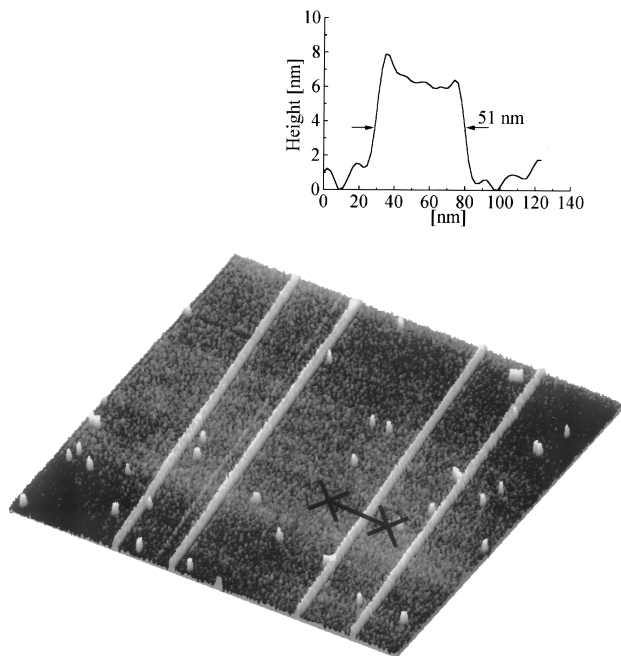


FIG. 4. AFM image ($5 \times 5 \mu\text{m}^2$) of lines directly written with a dielectric fiber probe without illumination. As illustrated in the inserted cross-sectional profile, the linewidth is ~ 50 nm. The lateral separation between the forward and backward scanning direction is clearly seen.

range 110–130 nm. The widths of the side lines are 200–230 nm.

In Fig. 4 a hydrogen-passivated silicon surface was scanned without light coupled into the probe. After scanning, the sample was again etched 30 s in KOH at room temperature. Two pairs of lines are seen, each pair being due to one forward and one return scan, the two being separated by 720 nm due to creep. The linewidths are ~ 50 nm after KOH etch. In this case, the mechanism behind the hydrogen desorption may be an electrostatic potential between the probe and the amorphous silicon layer, which is electrically isolated from the Si(100) substrate. This mechanism is known from AFM experiments.²⁴

Using the same samples, we have written optically induced features using a laser direct-writing facility.²⁵ This system operates in the optical far field. A 100 mW laser beam ($\lambda=457.9$ nm) is focused to a $0.5 \mu\text{m}$ spot. Operating the system at optimum conditions, linewidths of $\sim 0.5 \mu\text{m}$ are measured in the amorphous silicon layer after KOH etch. The resolution obtained using the SNOM as a direct-writing facility is ~ 4 times higher, if the far-field contribution to the writing process can be suppressed. We are investigating the use of coated fiber probes to achieve an even higher resolution. In addition, an optical modulator can be included in the setup for generating complex two-dimensional patterns on the hydrogen-passivated silicon surfaces.

In conclusion, we have reported on a novel lithographic technique, where a reflection mode SNOM with an uncoated fiber probe has been used to locally oxidize a hydrogen-passivated amorphous silicon surface. With this technique, linewidths of down to 110 nm, induced by the optical near field, have been achieved after a KOH etch, although features are broadened in practice due to 250 nm wide sidebands produced by the optical far field. Further, linewidths of 50 nm have been directly written without optical exposure, apparently due to an electrostatic potential between the probe and the sample.

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