Advanced Lithography for Nanofabrication

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Nanostructures are defined to be ultrasmall structures and devices with dimensions less than or equal to 100 nm. Conventional methods for making thin film structures involve exposure of a thin layer of a polymer resist on a suitable substrate to define a pattern, which is than developed and used to fabricate the structures either by deposition, or by etching [1]. The feature sizes of the structures depend both on the resolution of the resist and the imaging method used to expose the resist [1,2]. The materials quality of nanostrustures is also an important factor. In many cases the nanostructures must be crystallographically perfect. Resistless methods of patterning, followed by epitaxial growth could significantly simplify nanofabrication by eliminating a number of processing steps associated with the application, exposure, development, and removal of the resist. The advantage of epitaxial growth is that unlike etching, it is less prone to produce damage in the regions adjacent to the structures. The molecular size effect with polymer based resists such as PMMA is believed to be a significant factor in limiting the resolution ("grain size") in electron beam lithography (EBL) to 10 nm. Surface adsorption layers such as the hydride layer on the Si surface are characterized by relatively strong chemical bonding which produces a highly uniform coverage that terminates at a single monolayer. Because of these properties surface adsorption layers are attractive candidates as ultrathin, ultrahigh resolution resists for electron beam patterning.

The scanning tunneling microscope (STM) has recently been widely used for modification of surface adsorption layers including the surface hydride layer. Linewidths, down to 1 nm have been demonstrated on hydrogen passivated silicon surfaces [3]. However, because of the slow writing speed and the narrow field of view, it is unlikely that STM patterning will become useful for high volume pattern replication. In addition, the STM fabricated ultrahigh resolution patterns were found to be too frail to survive the subsequent pattern transfer steps. Fabrication of more robust structures was achieved at a loss of spatial resolution [4]. Recent advances in system design leading to increased throughput combined with a suitable resistless medium could make conventional electron beam based methods attractive for ultrahigh resolution (sub 0.1 μm) lithography. In this paper, we report on results concerning electron beam induced patterning of the surface hydride layer on silicon, using a scanning electron beam lithography (SEBL) system. The dependence of the linewidth on accelerating voltage, electron exposure dose, and sample thickness was explored to determine the mechanisms that govern pattern formation. The results achieved with silicon hydride have general significance and are believed to be applicable to other adsorpion layer/substrate combinations. The objective of this research is to artificially generate ultrahigh resolution lateral chemical selectivity on the growing surface which is to be used in subsequent epitaxial growth of nanostructures in a process know as selective area epitaxy (SAE).

The SEBL system consists of a commercial SEM, an Amray model 1400 that was interfaced for external control of the electron beam positioning, blanking, and exposure time. The external voltages required for electron beam positioning are derived by a 16-bit digital-to-analog controller. The resolution of the pattern generator under these conditions is 1.5 nm. This is lower than both the beam diameter and the resolution limit of PMMA. The SEBL is operated with either a tungsten filament or a LaB_6 emitter. The beam current is in the range of 50-100 pA. Typical electron exposure doses are in the range of 1-4 μC/cm. The pressure in the turbomolecular pumped sample chamber is in the low 10^{-6} Torr range. The baseline performance capabilities of the SEBL were determined using conventional EBL. Minimum linewidths for gold lines of 50 nm were routinely achieved using PMMA resist and lift-off.

The surface hydride layer is a uniform adsorption layer that forms naturally on the silicon surface. The hydride layer can be formed easily, either *ex situ* by a dilute HF dip that is a standard sample preparation step, or *in situ* it occurs during thin film growth using hydridic source gases. The passivating property of the silicon hydride is the basis of SAE. By exposing the hydride layer to a suitably focused particle beam, the hydride coverage can be locally removed, and a pattern of highly reactive, depassivated (bare) silicon formed. Thus, the function of the electron beam is to chemically alter the passivated surface of the Si substrate. *Simultaneous exposure to a source gas will produce selective epitaxial growth only at the depassivated sites.*

Following standard solution cleaning using trichloroethylene, aceton, and methanol the Si substrates were oxidized in a UV photoreactor to remove the remaining hydrocarbons and to oxidize any metallic impurities. The silicon hydride layers were prepared by a dilute (5-10 %) HF dip of the UV oxidized samples. Following

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the HF dip the surface is passivated by a uniform silicon hydride layer. Hydride passivation of the surface was confirmed by scanning Auger microprobe analysis. No surface contaminants such as carbon or oxygen were observed.

Electron beam induced patterning was conducted in the SEBL system. To elucidate the mechanism of pattern formation the effects of the electron acceleration voltage, the electron exposure dose at a fixed acceleration voltage (30 kV), and the sample thickness on the resulting linewidth were investigated. The patterns that form in the SEBL are at most only a few monolayers thick and provide insufficient contrast for direct observation by SEM or optical microscopy. For linewidth studies and observation purposes the patterns were transferred by anisotropic wet etching in tetramethyl ammonium hydroxide. Several examples of test patterns and arbitrary features are shown in Fig. 1.

From analysis of the linewidth data the following trends have been extracted. At 30 kV, and an electron exposure dose of 0.75 μC/cm the linewidth initially increases with electron exposure dose and saturates past 1.9 μC/cm. The linewidth increases from 0.1 μm at 30 kV to 0.24 μm at 10 kV at a same electron exposure dose. This effect strongly suggest that the exposure is caused either by backscattered or by secondary electrons. Similar line broadening with decreasing accelerating voltage is found in resist based EBL that is known as the proximity effect.

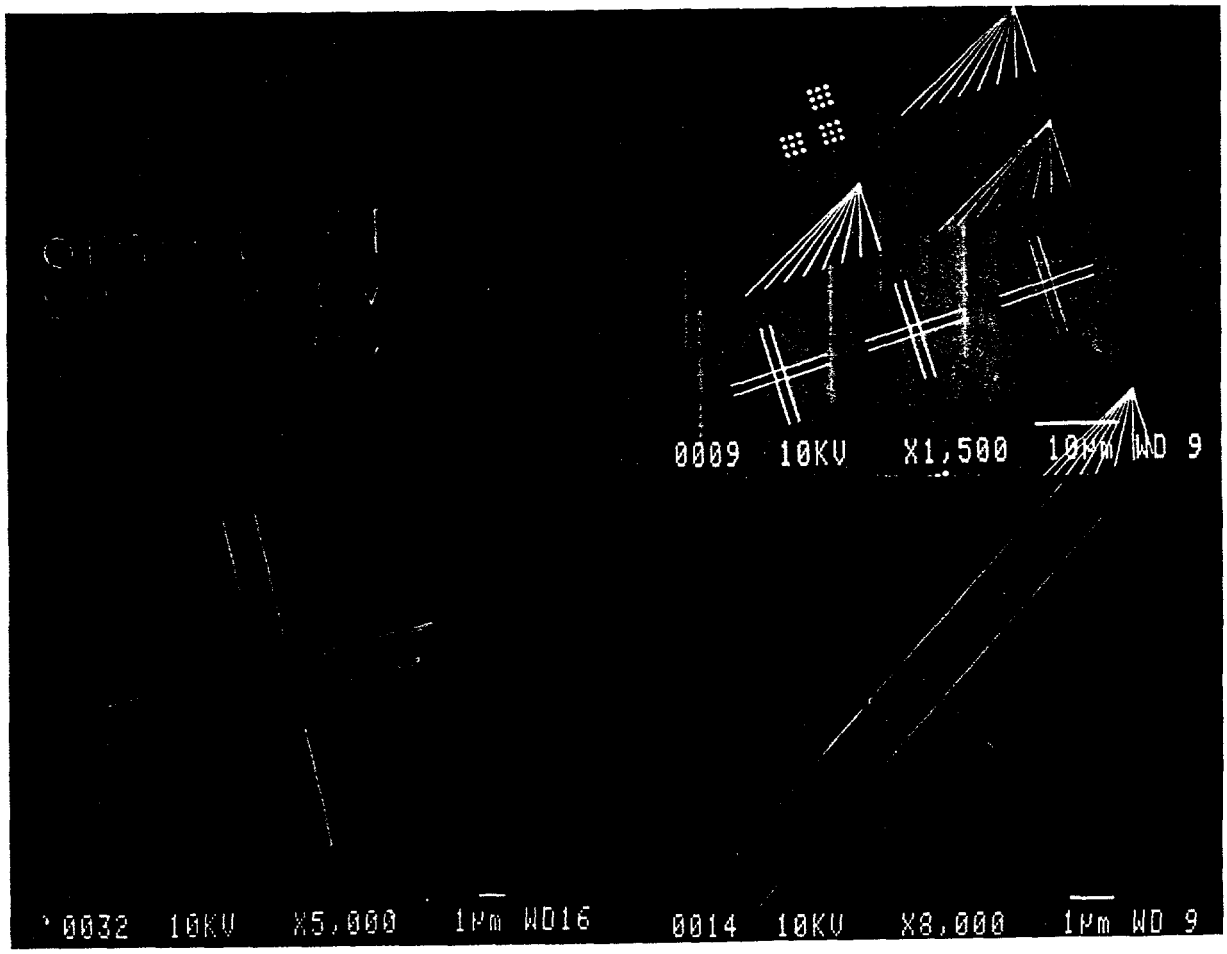

FIG.1.**(Top left)** Illustration of the arbitrary pattern capabilities with hydride lithography. The linewidths in this optical micrograph are 0.2 μm.
(Top right) Test patterns consisting of lines and dots to evaluate the electron exposure dose effects. Patterns produced with electron exposure doses of 1 μC/cm, 2 μC/cm, and 3 μC/cm are shown. The thicker lines correspond to a higher dose.
(Bottom left) Illustration of the acceleration voltage dependence of the linewidth. The linewidth at 10 kV is 0.24 μm.
(Bottom right) The linewidth at 30 kV is 0.1 μm.

The role of the backscattered electrons in pattern formation was explored by patterning a tapered silicon sample using a 30 kV acceleration voltage. Ion milling was used to fabricate a sample with gradually increasing thickness away from a central opening of about 100 microns in diameter. The thickness changes from about 1 μm near the central opening to the actual thickness of the wafer. If backscattered electrons play a significant role in image formation one would expect a gradual change in the linewidth as the writing beam is scanned from the thin toward the thick region of the sample. Preliminary results on these tapered substrates show no changes in the linewidth with thickness, suggesting that backscattered electrons are not a major factor in the pattern formation mechanism.

In conclusion, the passivating hydride layer on silicon surfaces was used as a prototype to explore the feasibility of electron beam patterning of surface adsorption layers for nanolithographic applications . The patterns obtained by hydride lithography were continuous with a minimum linewidth of 0.1 μm. The initial results indicate that further improvements in the resolution of hydride lithography can be achieved with better understanding and control of the mechanisms governing the patterning process.

This research was sponsored by the Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp., for the U.S. Department of Energy, under contract DE-AC05-96OR22464.

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[1] W.M. Moreau, *Semiconductor Lithography Principles, Practices, and Materials* Plenum Press, New York, 1988.
[2] A.N. Broers, Proc. R. Soc. Lon. A **416**, 1 (1988).
[3] J.W. Lyding, G.C. Abeln, T.-C. Shen, C. Wang, and J.R. Tucker, J. Vac. Sci. Technol. **B 12**, 3735 (1994)
[4] P. Fay, R.T. Brockenbrough, G. Abeln, P. Scott, S. Agarwala, I. Adesida, and J.W. Lyding, J. Appl. Phys. **75**, 7545 (1994).