Direct Electron-Beam Patterning of Surface Coatings and Sacrificial Layers for Micro-Total Analysis Systems

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Carbon-based materials were patterned by electron-beam lithography for applications in micro-total analysis systems. A heat-depolymerizable polycarbonate (HDP) layer on silicon was demonstrated as a sacrificial layer for forming microfluidic channels. Lines of HDP were patterned by electron beam lithography and an oxide capping layer was deposited. HDP was then removed from the oxide channels by heating. Coating materials for micro-total analysis systems were also investigated. Self-assembled monolayer coatings were directly patterned by electron beam lithography, then chemically treated to have the desired surface properties. The resulting chemical templates were used to pattern biomolecules and particles of interest for micro-total analysis systems.

Keywords: electron-beam lithography, microfluidics, self-assembled monolayers, heat-depolymerizable polycarbonate

1. Introduction

Research into micro-total analysis systems (micro-TAS) for chemical analysis in chip-based devices has intensified over the past decade [1]. Methods for making microfluidic chips include etching channels in the wafer and bonding a glass lid [2], and patterning a sacrificial amorphous silicon [3] or oxide [4] layer, which provides support while a durable capping layer is applied. The sacrificial layer is then removed by a selective chemical etch. In the present work, a heat-depolymerizable polycarbonate (HDP) sacrificial layer was tested instead [5]. Although the HDP material was not designed as an electron beam resist, we found that it could be patterned directly by electron beam lithography, rather than through a resist mask as in the silicon and oxide methods. Another advantage of the HDP method is that the polymer decomposes into non-toxic monomer units when heated, as shown in Figure 1. In the HDP process, the usual chemical etch for sacrificial layer removal can be substituted by a more environmentally friendly heating step.

![Fig. 1: Thermal depolymerization process.](image)

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Chemical surface treatments within micro-TAS devices can alter their performance and are sometimes central to their function, as in DNA microarray systems [6] and diffraction-based biosensors [7]. SAMs are only 1 to 5 nm thick, but they are extremely versatile coatings that have been used as chemical etch masks [8,9], templates for electroless plating [10], and control surfaces for liquid crystal orientation [11, 12]. However, a more interesting feature for micro-TAS applications is that SAMs can be tailored to attract specific biomolecules to certain regions, or to prevent adhesion from occurring. Confining molecules to a small region can increase the signal in micro-TAS devices having a small observation volume [13]. This paper will discuss our work with electron beam lithography patterning of self-assembled monolayer (SAM) coatings relevant to micro-TAS. We found that chemically active SAM coatings on silicon could be inactivated by electron beam damage to the reactive groups at the SAM surface [14]. SAMs in this study were 2-aminopropyltriethoxysilane (APTS) and (aminoethylaminomethyl)phenethyltrimethoxysilane (PEDA). Figure 2 shows a diminishing Auger signal for nitrogen during continued electron beam exposure of amine-terminated SAMs, indicating removal of the nitrogen-containing amine groups. Subsequent patterning research used electron beam lithography to remove inert SAM molecules, replacing them with chemically active molecules [15]. In addition to patterning biomolecules, we have used SAM templates to pattern several kinds of particles, including metal colloids [14], polystyrene spheres [14,15], CdSe nanocrystals [16], and 1-micron diameter glass spheres. Covalent binding of the glass spheres was strong enough to hold the spheres in place while an electron beam resist layer was spun, and a resist pattern was aligned and developed over the particles. Combining the polymer sacrificial layer method with patterned particles may generate a new class of micro-TAS devices containing trapped particles having useful mechanical, chemical, or luminescent properties.

2. Method

2.1. HDP Channel Method

Details of HDP synthesis are given in [17], and further details about optimizing the electron exposure conditions and capping layer deposition process appear in [5]. 140 nm thick HDP films were made on silicon or silicon nitride coated wafers by spin-coating a solution of 5% HDP in toluene at 3000 RPM. Films were solvent-removal baked at 90 °C for 1 minute and patterned in a low-energy electron beam lithography system. Typical conditions to clear resist from the exposed areas were a beam energy of 5 kV and an exposure dose of 150 µC/cm². Films were developed by immersion in isopropanol for one minute. A 500 nm thick SiO₂ capping layer was then sputter coated on top of the HDP pattern. The temperature was kept below 300 °C during sputtering by periodically stopping to allow the wafers to cool. After sputter coating, the sample was placed on a hotplate at 300 °C for 1 hour, allowing the HDP to vent from the oxide tubes through holes provided in the back side of the wafer.

2.2. Electron Beam Patterning of SAMs and Attachment of Other Materials

Chemically reactive APTS monolayers were formed on silicon substrates by immersion in a solution of 50 ml methanol, 2 ml acetic acid, 2 ml water, and 1 ml APTS for 2 hours. Further details of the monolayer formation and patterning process appear in [14]. Monolayer samples were patterned with an electron dose of 300 µC/cm² at 1 kV beam energy. Following patterning, samples were immersed in a solution of 30 µl NeutrAvidin protein-coated fluorescent beads in 3 ml BlockAid buffer solution (Molecular Probes, Inc.) for 2 hours to attach the protein beads to unexposed regions of the SAM film.

A reverse-tone monolayer template process described as "backfilling" is detailed in [15]. In one

![Fig. 2. Area under nitrogen Auger peak vs. electron dose at 10 kV for APTS and PEDA monolayers.](image-url)
of our backfilling experiments, an octadecanethiol (ODT) monolayer was formed on gold-coated silicon wafers by overnight immersion in a 1 mM solution of ODT in ethanol. ODT is a linear 18-carbon chain with a sulfhydryl end that binds to gold and a methyl end that produces a hydrophobic monolayer surface. The monolayer sample was patterned with an electron dose of 200 µC/cm² at a beam energy of 2 kV. Carbon debris was cleaned from exposed areas by 45 seconds in a UV ozone cleaner (UV Ozone Systems Inc.), and the sample was immersed in a 10 mM solution of cysteamine (Fluka) in water for 2 hours. Cysteamine binds to gold with a sulfhydryl group, and has a terminal amine group that can react with other molecules. The samples were ultrasonically cleaned in water for 1 minute to remove excess cysteamine, then placed in a solution of 5 µl glass beads (1 μm diameter "covalent binding" beads, proprietary aldehyde-based coating, Xenopore) in 1 ml of 10 mM morpholineethanesulfonic acid buffer (Acros Organics) for 2 hours. The samples were then water rinsed and dried with nitrogen. Dried samples were coated with a 1.2 micron thick polymethylmethacrylate (PMMA) electron beam resist layer by spinning an 11% PMMA solution in anisole onto samples at 3000 RPM for 30 seconds. Previously patterned alignment marks allowed a pattern to be exposed in registry with the glass bead pattern. PMMA was exposed at 20 kV using an electron dose of 200 µC/cm² and developed in a 1:3 solution of methylisobutylketone/isopropanol.

3. Results
3.1 HDP Channels
Figure 3 shows a 1 micron wide oxide channel formed by the HDP process. The channel was injected with fluorescein dye and viewed in an optical fluorescence microscope. To lessen the exposure time, the channel was defined by drawing 100 micron length boxes rather than filled rectangles. Unexposed box centers are visible in the image as light gray regions beside the channel.

3.2 SAM Chemical Templates
Figure 4a is an optical fluorescence micrograph of the APTS sample with 40 nm diameter NeutrAvidin fluorescent beads (not individually resolved in this image). The electron-beam exposed areas are black rectangles 10 μm wide and 50 μm long. The fluorescent protein-coated beads attach in the surrounding areas where surface amines have not been damaged by electron beam exposure. Figure 4b is an optical micrograph of the glass beads attached to four 10 μm square cysteamine pads that have been backfilled into exposed regions of an ODT monolayer on gold. The pointed vertical bars are the PMMA pattern which was aligned with the monolayer pattern after the glass beads were attached. The PMMA bars cover the glass beads and pads.

4. Discussion
Channels of total length 1 mm and width 1 micron were successfully formed by the HDP process. For smaller channel widths (400 nm and below) some plugged areas were seen, indicating that the bakeout process may need to be intensified for small geometries. A lower temperature capping layer deposition process such as plasma-enhanced chemical vapor deposition (PECVD) would be more suitable for the HDP material.
Direct patterning of amine-terminated SAMs produced good chemical templates, as indicated by the patterned avidin-coated beads. However, if small reactive areas were needed, it was necessary to write a large negative area around the feature, which is impractical in electron beam lithography. Backfilling reactive monolayers into patterned inert monolayers was a more versatile process. Covalent binding of the aldehyde-coated glass beads to the amine-backfilled regions was strong enough to hold the beads in place during spin-coating of viscous electron beam resist and further processing.

5. Conclusions
Combining chemical templates with micro-channels may lead to interesting new micro-TAS devices, including channels with patterned, chemically active biomolecules or channels containing trapped particles for mixing, valving, or other applications. Delicate biomolecules may need to be patterned after channel construction is complete, but the glass bead process in figure 4b illustrates that channels might be formed directly over patterned particles by a polymer sacrificial layer process.

In this work, HDP and SAM materials were directly patterned by electron beam lithography. This is in contrast to other microfabrication materials which must be patterned through a resist mask. Photopatterned versions of these materials would not have the high resolution features of electron-beam lithography, but could be processed more quickly. Photolithography of SAMs has been investigated by others [18]. However, HDP is transparent to ultraviolet light, so it would be necessary to photosensitize the material. Processing speed is important as micro-TAS devices are desired to be mass produced and disposable.

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