A Versatile Nanopatterning Technique Based on Controlled Undercutting and Liftoff

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Nanopatterning techniques have applications across a wide range of experimental sciences, from controlling cell growth and function[1] to improving the efficiency of thin film solar cells.[2] Approaches developed by the microelectronics industry such as photon-, ion- and electron-beam lithography are highly refined, producing features with dimensions of just tens of nanometers. Unfortunately, the cost of these methods prohibits access to many in the scientific community. As a result, the last two decades has seen an exponential increase in publications on unconventional nano-patterning techniques[3] which provide cheaper, but restricted ways of fabricating nanostructures. These include soft,[4] nano-imprint,[5] block copolymer,[6] and scanning probe[7] lithography. Here, we report on a new edge-based technique that extends a controlled undercutting method, first proposed by Love et al.[8]

The Love et al.[8] method is limited to creating trenches by dry etching with low bias plasmas due to the use of a thin metal masking material. The novelty of our approach is the introduction of a polymer buffer layer between the substrate and metal masking layers. This permits more varied processes than simple trench formation (e.g., liftoff) and greater processing latitude (e.g. the use of high bias plasma etching). Liftoff is an essential technique for patterning hard-to-etch materials with low contamination. Masks that can withstand physically aggressive dry etches are required to pattern many materials. Such robust polymer masks ensure excellent process yields.

Edge lithography encompasses a wide class of methods which exploit the boundaries of pre-existing structures to define new, smaller patterns. Common examples of edge techniques include near-field phase shift,[9] controlled undercutting,[8] side-wall transfer,[10,11] edge spreading[12] lithography and topographically defined defects in self-assembled monolayers.[13] Edge lithography is a useful but limited method of extending the resolution of existing lithographic techniques. For instance, self-aligned double patterning[14] is a technique that allows 45 nm lithographic processes to be used at the 22 nm node. Since edge lithography is limited to producing features that follow a pattern's perimeter, subsequent lithographic steps are required to trim these to the desired shapes.

In controlled undercutting edge lithography, a masking material (e.g. aluminum) is deposited onto a substrate and a photoresist image is formed on top by standard photolithography (**Figure 1**a). The aluminum layer is subsequently dissolved by isotropic etching, performed for sufficient time such that the photoresist image becomes undercut (Figure 1b). More aluminum is then deposited by evaporation (Figure 1c) before the photoresist is dissolved (Figure 1d). This produces a patterned aluminum layer with openings that follow the perimeter of the original photoresist image. The aperture widths are defined by the degree of over-etching.

In this work, rather than using the aluminum directly as a mask, as previously reported,[8] the patterns are first copied into an underlying polymer layer. This is achieved by reactive ion etching (RIE) using an oxygen chemistry. The patterned polymer is more versatile than the original aluminum mask since (i) the polymer can be dissolved using organic solvents and (ii) it is possible to create high aspect ratio mask features with vertical side-walls. This is essential for accurate pattern transfer by physically aggressive dry etching methods.

The etch selectivity between the aluminum and polymer layers is very high due to the formation of a low sputter yield oxide on the aluminum surface. This permits the use of very thin aluminum films which is advantageous since the over-etching step can be precisely controlled and the grain size is small. The minimization of grain size is important to reduce the pattern line edge roughness.

The combination of an aluminum mask and a polymer layer permits four separate fabrication techniques as shown in Figure 1. Process 1 represents pattern transfer into the substrate by dry etching. Process 2 represents patterning by deposition and liftoff. Process 3 represents substrate patterning with an inverse polarity to the aluminum mask. Lastly, process 4 represents a double patterning liftoff technique.

During the dry etching of the polymer, the chamber pressure can be used to control the side-wall profile. At low pressures, the etching is highly anisotropic and the aperture in the aluminum mask is faithfully reproduced into the polymer layer (Figure 1e). In this instance, the patterned polymer forms a robust mask for etching the underlying substrate (Figure 1f). We have used such a process to fabricate nano-imprint masters from silicon and silicon dioxide substrates.

The resultant improvement in etch stability can be seen by comparing the scanning electron microscope (SEM) images shown in **Figure 2**a and Figure 2b. Both show trenches dry

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