Control of surface and line-edge roughness induced by plasma etching of Si-containing polymers

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Interface properties of polymers and their control become important at submicron scales, as polymers find widespread applications from micro- and nano-electronics to optoelectronics and other industrial fields. In this work, we address the issue of controlled modification of surface and line-edge roughness of Si-containing polymers when subjected to oxygen-based plasma treatments. Our experimental results reveal that, if plasma processing conditions are appropriately optimized, small values of surface and line-edge roughness can be obtained. This result is crucial for the potential use of these polymers for sub-100 nm lithography. On the other hand, when high topography is desired for application in sensor devices, plasma processing conditions can be modified to result in periodic structures of controllable size on Si-containing polymer surfaces.

1. Introduction

In recent years, roughening of materials has attracted considerable attention, as surface and interface roughness controls many important physical and chemical properties of films. Since roughness or the topography of surfaces in general results often from processing, this paper will address the issue of the dependence of surface and line-edge roughness (induced by plasma etching) on plasma processing conditions. Current literature relevant to the issue of plasma-induced roughness includes studies of, the roughening of plasma-etch fronts of Si [1-2], the evolution of the topography of lattice systems [3], and the formation and evolution of roughness on plasma-treated polymeric films [4-5].

Here, examples are presented of surface and line-edge roughness (SR, LER) of Si-containing polymers induced by oxygen-based plasma treatments. The dependence of the roughness and its structure on the gas composition, bias voltage, and electrode temperature, is considered. The behavior of Si-containing polymers such as poly-dimethyl siloxane and copolymers of silsesquioxanes is studied. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) are used to generate the surface images and statistical analysis is performed on the resulting images to quantify LER and to yield the scaling characteristics of SR and LER.

2. Experimental

Plasma processing was performed both in a NE 330 Nextral reactive ion etcher (RIE) and in a high density plasma (ICP) etcher (MET of Alcatel). Processing gases include pure oxygen and dilute mixtures with F-containing gases. In the ICP reactor, the temperature of the sample holder was well-controlled by means of thermostating the electrode, while heat transfer between the sample holder and the electrode was achieved by mechanically clamping the substrate holder to the electrode through backside helium contact. On the contrary, in the case of the RIE reactor, the samples were simply placed on the electrode without special care for providing good thermal contact with the electrode.

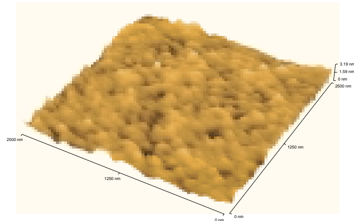
As Si-containing polymers, poly-dimethyl siloxane (PDMS) either pure or copolymers with 5% poly-vinyl-methyl-siloxane, and silsesquioxanes were examined. The etching behavior of PDMS, used as the imaging layer in bilayer lithography, has been reported in previous work [6] in terms of line-edge roughness. In this work, the surface roughness of PDMS as well as of PSQ as a result of oxygen plasma treatment is pointed out.

Surface roughness was measured on polymeric surfaces with a Topometrix TMX 2000 AFM system. Line-edge roughness of plasma developed PDMS lines/spaces was observed with a LEO 440 SEM.

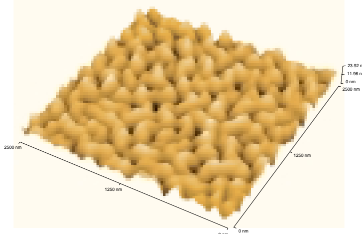
3. Results and discussion

3.1. Surface roughness

SR of the examined polymeric surfaces was found to depend mainly on the processing gas composition and the electrode temperature at which processing was performed. Especially for siloxanes, short treatment in F-containing plasmas before the



(a) ***T=15 •C, SR=0.4 nm***



(b) ***T=60 •C, SR=4.1 nm***

Fig. 1. AFM images of a PDMS surface. The roughness is mainly controlled by the plasma processing gas and the electrode temperature.

oxygen treatment at T=15 °C resulted in very small SR (rms values smaller than 1 nm), as shown in Fig. 1a. Fig. 1b illustrates an AFM micrograph of a PDMS surface exposed to a pure oxygen ICP plasma but at higher electrode temperature (T=60 °C). We found that SR increases by nearly an order of magnitude for temperature increase from-20 °C to 80 °C. Similar behaviour was observed for silsesquioxane surfaces, exposed to pure oxygen plasmas. We believe that the observed formation of undulated structures on Si-containing polymers is related to the relief of compressive stress developed between the bulk of the polymer film and the silica thin layer, grown on the polymer surface as a result of the oxidation of the Si-containing surface in the oxygen plasma [7]. Thus, differences observed between SR of RIE and ICP treated surfaces can be attributed to insufficient control of the polymer temperature in RIE plasma treatments.

Finally, the surface roughness of these surfaces is analyzed in terms of their scaling behaviour, and reveals periodic structures of sub-micrometer length scale, depending on the processing history of the surfaces.

3.2. Line-edge roughness

The effect of different etching chemistries and processing conditions on imaging layer line-edge roughness formation is demonstrated with the aid of SEM images and image analysis for quantifying LER.The importance of the processing gas composition in the reduction of the plasma-induced line-edge roughness of siloxanes is demonstrated in Fig. 2.

The significant LER shown in the top down SEM image of Fig. 2 (a) is formed after plasma development of the PDMS material in the pure oxygen plasma, due to the high selectivity of the etching of the bottom layer resist with respect to the Si-containing top resist. If a non-oxidizing and F-containing mixture is used in a first etching step, LER is significantly reduced, as shown in Fig. 2 (b). Detailed studies of the PDMS etching behaviour and the mechanisms involved in plasma-induced LER formation have verified that the selectivity of the etching process plays an important role to the magnitude of LER [6].

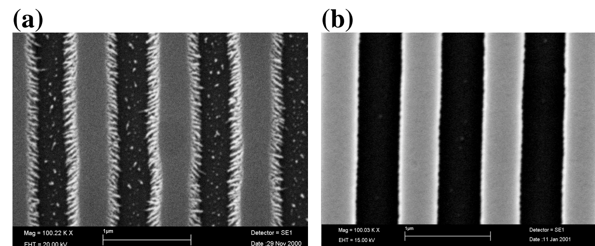


Fig. 2. SEM top-down images of nominal 0.5μm/0.5μm lines/spaces of a bilayer resist with PDMS as the imaging layer. The dry development of the bottom resist was performed in (a) a pure O_2 plasma, and (b) a O_2 plasma with an optimized first step in SF_6/He. Notice that the high LER obtained in the pure O_2 plasma is diminished with the F-containing first step

4. Conclusions

We have shown that oxygen-based plasma treatment of Si-containing polymers has significant effect on their material properties, and in particular on surface and line-edge roughness. These properties can be controllably varied, according to application requirements, depending on the plasma processing conditions.

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