Mechanisms of nano-roughness formation and evolution in plasma etching: application to Si etching

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A stochastic, Monte Carlo, simulation framework is used for the study of surface roughness formation during plasma etching. The plasma species interacting with the etched surface are categorized to reactive neutrals, depositing neutrals (etch inhibitors), and ions. The results are compared to experimental results of Si surfaces etched by SF_6 plasma. The experimentally observed dual scale nano-roughness and the surface roughness increase versus etching time are captured by the simulation framework.

Introduction

The control and understanding of roughness formation during plasma etching is of primary importance in micro- and nano-patterning technology. As the dimensions of fabricated features go down to the nano-scale, the roughness of their surfaces affects increasingly their physicochemical behavior and may degrade electrical, optical or other device performance. On the other hand, there are beneficial effects of high surface roughness, e.g., in the fabrication of super-hydrophobic surfaces [1].

A common finding of past works devoted to the experimental and theoretical investigation of roughness origins and formation on plasma etched Si surfaces was the increase of the surface roughness, i.e., the root mean square (rms) roughness, versus etching time [2,3,4]. In a previous work [2], by using a (1+1)D stochastic simulation framework, we also demonstrated that dual scale roughness is captured by a model including reactive neutral species, ions and etch inhibitors; the latter may come from the sputtering of electrode and/or reactor-wall material ("hard" inhibitors).

The aim of this work is to quantitatively reproduce all surface roughness parameters by a) refining model parameters, i.e., sticking probabilities and yields, b) including another type of etch inhibitors ("soft" inhibitors) produced in the bulk phase of the plasma reactor, c) taking into account surface diffusion, and d) using a (2+1)D simulation tool. In addition, atomic force microscope (AFM) images of Si surfaces etched by SF_6 plasma are characterized and compared to the simulation results.

Experimental measurements

An inductively coupled plasma reactor of Alcatel was used for the plasma etching of Si samples. SF_6 plasma was used. The topography of the etched Si surfaces is measured by Atomic Force Microscope (AFM) (Nanoscope III) at several time instances during etching. In Fig. 1, 2 AFM images of Si surfaces after 4 and 16 minutes of etching are shown. Humps, shown as sharp peaks due to the scale of z axis in AFM images, are observed on the etched surfaces. Note that this is not grass, the aspect ratio of these humps (ratio of the height to the width of the humps) is low and they could be hardly seen in Scanning Electron Microscope (SEM) images. In the height distribution, there is a long tail due to these humps (see embedded the height distributions for each surface). The roughness of the surfaces of Fig. 1 can be characterized as dual consisting of long wavelength regions and humps on top of them. Both the height and the width of these humps are increasing during etching. In Fig. 2c, the evolution of root mean square (rms) surface roughness is shown versus etching time.

The simulation framework

A stochastic simulation framework in (1+1)D and (2+1)D is developed. The etched film is represented by cells. Both reactive and depositing ("hard" or "soft" inhibitors) neutral species, as well as, ions are the particles which interact with the etched film. The trajectory of each particle is calculated until sticking on a cell. Shadowing effects and reemission and surface diffusion of particles are taken into account. The interaction of particles with the

topography cells is defined by a) the sticking probability and b) the etching yield. Monte Carlo method is used to sample stochastic variables from probability distributions defining the initial position and direction of the particle, the etching yield, the reemission probability, and the direction of reemitted particles.

Results

In Figs. 2b and 2d, a (1+1)D profile and the rms surface roughness versus etching time, both resulted from simulation, are shown and compared to pertinent experimental measurements (Figs. 2a and 2c). The predicted humps in the simulation profiles exhibit a higher aspect ratio. This simulation result can be improved by refining model parameters. In Fig. 3, a typical height distribution of the profiles resulted from the simulation is shown. The tale is due to the humps on the profile, as in the experimental measurements.

Conclusions

The increase of rms roughness versus time is captured by the simulation. In addition, the role of etch inhibition is very important in the surface roughness formation during plasma etching. In one hand, "hard" inhibitors coming the sputtering of the electrode or the reactor-wall is a possible explanation for the dual scale roughness experimentally observed. On the other hand, based on current research progress, "soft" inhibitors, produced in the bulk plasma (e.g., radicals containing S) seem to cause the growth of the width of the humps formed on the surface.

References

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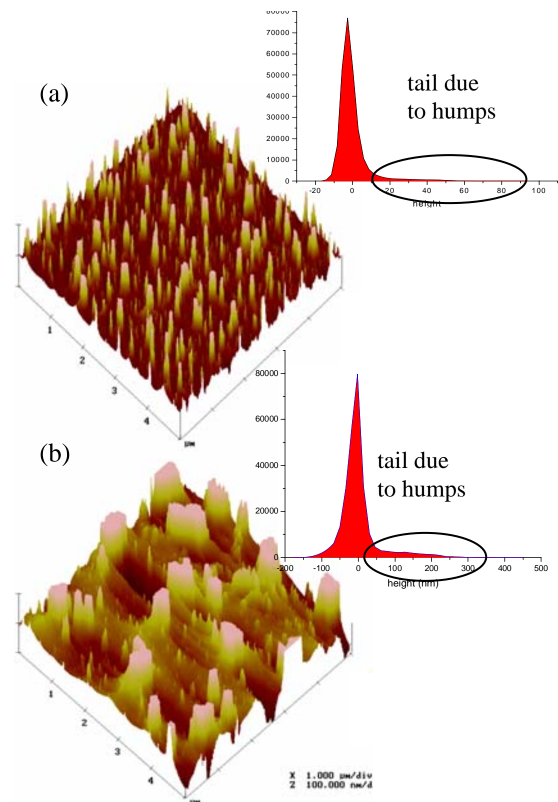

Fig. 1. AFM of Si surfaces etched by SF_6 plasma after a) 4 minutes (z scale: 45 nm/division) and b) 16 minutes (z scale: 100 nm/division). The height distributions are shown embedded. Please note that the humps or nano-humps have a low aspect ratio and they are not grass.

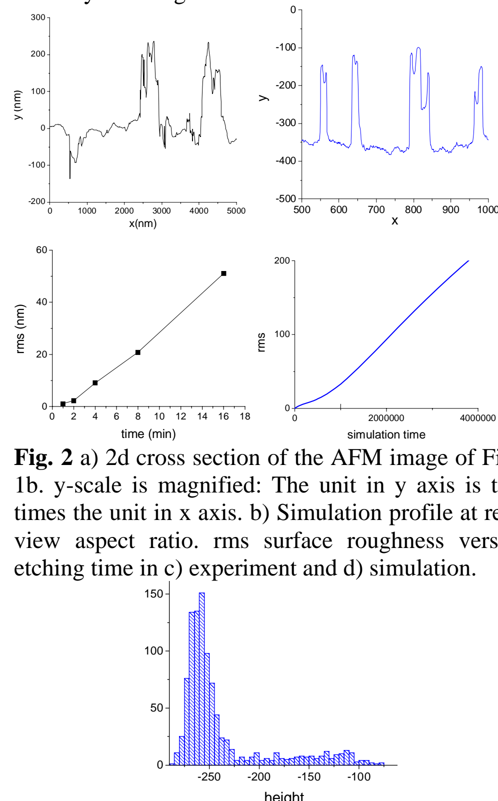

Fig. 2 a) 2d cross section of the AFM image of Fig. 1b. y-scale is magnified: The unit in y axis is ten times the unit in x axis. b) Simulation profile at real view aspect ratio. rms surface roughness versus etching time in c) experiment and d) simulation.

Fig. 3. A typical height distribution resulted from simulation. As in the experimental measurements, the tale is due to the humps on the etched profile.