Stochastic Plasma Charging of Nanopatterned Dielectric Surfaces

Jason A. Kenney, Eunsu Paek, and Gyeong S. Hwang

***Abstract*—A 2-D simulation of the plasma bombardment of high aspect ratio dielectric structures is used to demonstrate stochastic charging behavior arising as absolute dimension decreases from 500 to 50 nm. Statistical analyses are then performed after the system has evolved beyond initial charging to indicate the regions of high variability in potential and to provide representative snapshots of mean and extreme potentials within the structure.**

***Index Terms*—Plasma bombardment, stochastic processes, surface charging.**

DIRECTIONALITY differences between impinging ions and electrons are known to give rise to differential surface charging of patterned dielectric or weakly conducting materials during plasma exposure. Earlier theoretical studies [1] mostly focused on describing the mean behavior of surface charging at the micron scale or larger. However, as device feature sizes shrink into the nanometer-scale regime, the influence of an individual charge transferred to the surface will be larger, leading to an increase in the variability of potentials within the charging area. This leads to the question of whether a true steady-state-like behavior will be reached for high aspect ratio dielectric nanostructures or will large oscillations in potential lead to essentially stochastic behavior.

In this paper, we demonstrate the possibility of stochastic behavior with a decreasing feature size based on extensive Monte Carlo simulations of plasma charging. The modeling and simulation methods are described in detail elsewhere [2]. Briefly, ions and electrons emerge from a plane above an open-bottomed dielectric trench structure. Collisions with the structure transfer the appropriate charge to the surface, with potentials within the entire simulation domain updated before the consideration of the next particle. Energies are recorded for particles which pass through the trench region and exit a plane that is opposite the initiating plane. Potential is calculated by using the Laplace equation, with Gauss' law used to relate the surface charge. Surface conduction is also considered, although on a separate timescale from that of particle generation.

For the simulations, we assume equal fluxes of ions and electrons arriving at the surface, giving an equal probability for generating either species. Electrons are sampled from a Boltzmann distribution with an average temperature of 4 eV. Ion energies are the composite of a thermal component (Boltzmann, average temperature is 300 K) and a directed component, which is sampled from a bimodal energy distribution with peaks at 15 and 48 eV. All of the dielectric structures considered have an aspect ratio of five, with widths varying from 500, 100, to 50 nm. Particles emerge from a plane four times this width above the structure. The sheet resistance of the structure is $1.0 \times 10^{20}\ \Omega$, giving minimal surface conduction.

The upper panels shown in Fig. 1 describe the evolution of ions reaching the exit plane with extrusion plots. The number of exiting ions was recorded after every 20 000 particles, which is binned according to the exit energy. For both the 100- and 500-nm cases, a significant number of low energy ions are able to pass through the structure during the initial stages, considering that the structure is first charging. Following this regime, low energy ions are no longer able to overcome the potential barrier within the 500-nm structure, and can only periodically overcome this for the 100-nm case. In contrast, the 50-nm structure allows these low energy ions to exit throughout the simulation, owing to the increased importance of singular particles to influence the surface charge.

Two statistical analyses were performed on 500 potential snapshots taken every 5000 particles after 7.5×10^6 particles had already impinged (well after initial charging), as shown in the lower panels of Fig. 1. The larger contours describe the standard deviation in the potential as measured locally (σ_{Loc}) at locations within the trench structure. From these contours, it is apparent that potentials change more dramatically at smaller dimensions as expected but also that the region of highest variability moves down the structure sidewall as the width decreases. The smaller contours are representative snapshots of the mean and extreme potentials seen in the trench, as determined by a statistical analysis of the average potential within the entire area of the trench for each of the 500 samples. After finding the mean (χ) and standard deviation (σ), the snapshot with the closest average potential to the desired expression $(\chi, \chi \pm 2\sigma)$ was determined. From these contours, one can readily understand the aforementioned extrusion plots. At 500 nm, there is little variability in the potential within the trench, and a constant potential barrier to low energy ions exists. At 100 nm, the lower potential extreme allows low energy ions to pass, but on average, the potential barrier at the trench exit is too large for them to exit. A further reduction in the trench width to 50 nm shows both average and lower extreme behaviors that are conducive to the movement of low energy ions.

Manuscript received December 2, 2007; revised January 29, 2008. This work was supported in part by NSF under Grant CTS-0650536.

J. A. Kenney is with Applied Materials, Inc., Sunnyvale, CA 94085 USA.

E. Paek and G. S. Hwang are with The University of Texas at Austin, Austin, TX 78712 USA (e-mail: gshwang@che.utexas.edu).

Digital Object Identifier 10.1109/TPS.2008.927030

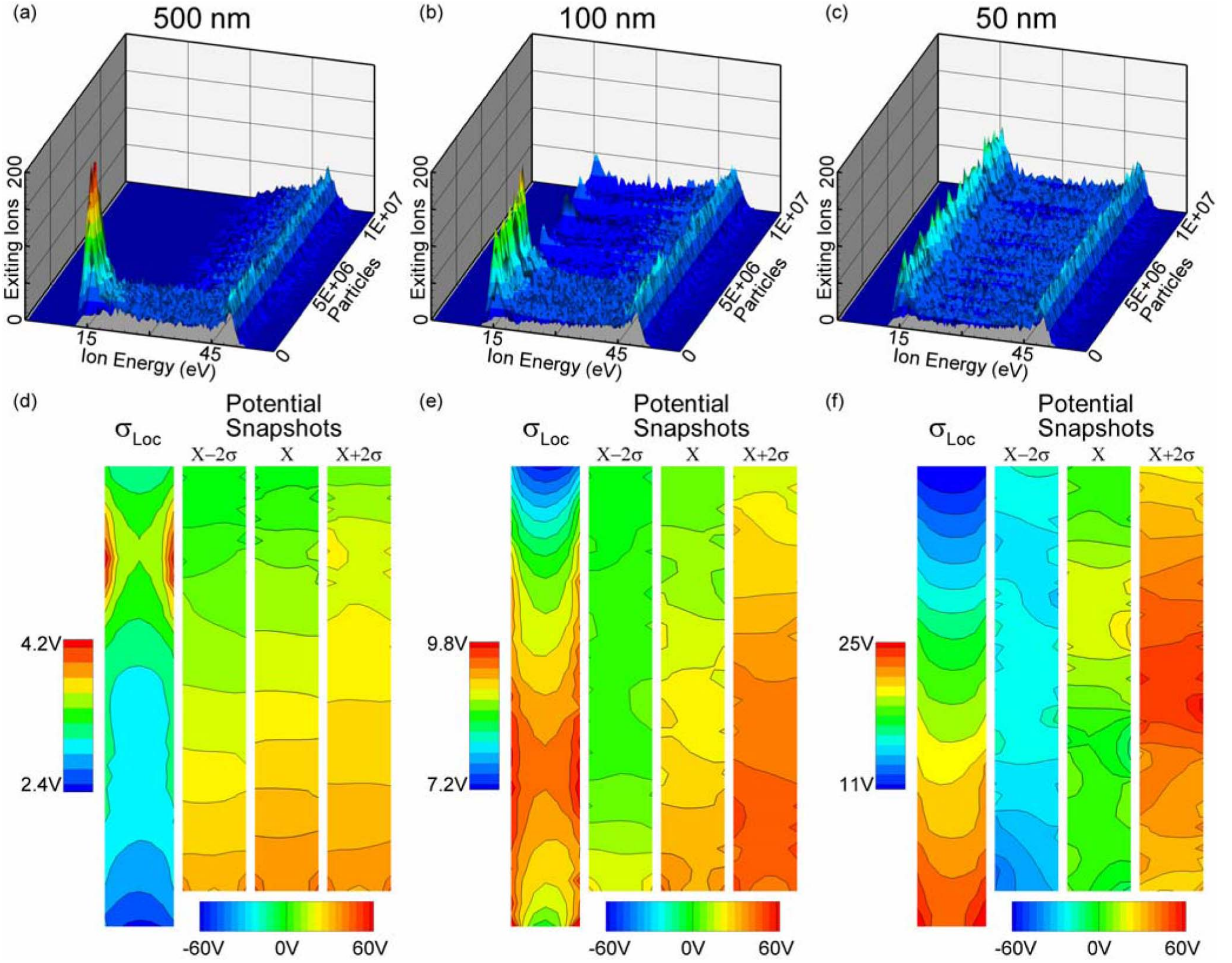

Fig. 1. (a)–(c) Extrusion plots showing the number of ions exiting the high aspect ratio structure with the exiting energy and the total number of generated particles for 500-, 100-, and 50-nm-wide structures, respectively. (d)–(f) Local standard deviation in potential (σ_{Loc}) and snapshots of the mean (χ) and extreme $(\chi \pm 2\sigma)$ potential behaviors within the 500-, 100-, and 50-nm-wide structures, respectively. Analyses were performed on 500 samples taken every 5000 particles, following 7.5×10^6 particles that were generated.

In summary, we demonstrate the possible effect of pattern dimensions on the plasma charging of dielectric nanostructures. The improved understanding will assist in explaining and predicting the complex behavior of surface charging and subsequent surface modifications in the application of plasma techniques to the fabrication of future nanostructure-based devices.

REFERENCES

[1] G. S. Hwang and K. P. Giapis, “On the origin of the notching effect during etching in uniform high density plasmas,” *J. Vac. Sci. Technol. B, Microelectron. Process. Phenom.*, vol. 15, no. 1, pp. 70–87, Jan./Feb. 1997.

[2] J. A. Kenney and G. S. Hwang, “Prediction of stochastic behavior in differential charging of nanopatterned dielectric surfaces during plasma processing,” *J. Appl. Phys.*, vol. 101, no. 4, p. 44 307, Feb. 2007.