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Plasma-Surface Interactions for Materials Nanofabrication and Space Propulsion: A Unified Study for Technology Developments and Future Progress
プラズマ・表面相互作用の研究展開：ナノ加工プロセスと宇宙航行推進

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A better understanding of plasma-surface interactions is indispensable for utilizing plasmas in hand. This paper presents an overview of the evolution of our understanding of several phenomena associated with plasma-surface interactions in the fields of materials nanofabrication and space propulsion. A numerical approach to reproduce plasma-surface interactions and profile evolution relies on a continuum model, discrete or Monte Carlo-based model, and also classical molecular dynamics simulation, to promote a unified study of the interactions for future technological developments.

1. Introduction

Plasma-surface interactions can occur in a number of research and application fields of plasma: materials processing, lighting, display, actuator, welding, controlled nuclear fusion, and space development. The interactions involve a number of physical and chemical issues of enormous complexity that occur on surfaces, such as surface chemistry of neutrals, ion-solid and radiation-solid interaction physics, materials science, and plasma physics of the sheath. It is often assumed in low-pressure plasmas that the positive ions enter the surface after being accelerated through the sheath thereon, while neutrals tend to enter the surface isotropicallly or thermally without being influenced by the sheath. Moreover, the short-wavelength radiation incident on the surface often causes some modification of surfaces as well as photoelectron emission therefrom. The phenomena of interest have evolved from being macroscopic or phenomenological to microscopic or atomistic.

This paper presents an overview of the evolution of our understanding of several phenomena associated with plasma-surface interactions in the fields of materials nanofabrication and space electric propulsion, with emphasis being placed on a unified study for technological developments and future prospects. In materials processing [1], the plasma-surface interactions on substrates are indispensable to achieve the processing (etching, deposition, and modification), while the interactions on chamber walls and other nearby surfaces are required to be understood, to control the concentration of ions and neutrals in the plasma. In electric or plasma propulsion system [2], the interactions of propellant ions with chamber walls and electrodes erode them over time, which tends to limit the lifetime of thrusters in operation.

2. Materials Nanofabrication

Dry or plasma etching is an indispensable processing technique in the fabrication of modern microelectronic devices. Increasingly strict requirements are now being imposed on plasma etching technology, as ultra-large-scale integrated (ULSI) circuit device dimensions continue to be scaled down to << 100 nm [3–5]. The requirements include the precise or nanometer-scale control of etched profile, critical dimension (CD), roughness, and their microscopic uniformity (or aspect-ratio dependence), together with that of etch rate, selectivity, and damage.

In front-end-of-line (FEOL) processes, the nanometer-scale control of Si etching in chlorine- and bromine-based plasmas is indispensable for the fabrication of gate electrodes and shallow trench isolation, through suppressing profile anomalies of sidewalls and bottom surfaces. In practice, sidewall anomalies, such as tapering, bowing, footing (or corner rounding), and notching, largely affect the CD and its difference between isolated and dense patterns and also between *p*- and *n*-type gates. The roughness or ripple on sidewalls is also a critical issue to be resolved, because the resulting line edge roughness (LER) and line width roughness (LWR) on feature sidewalls are responsible for varied gate widths and thus the variability of transistor performance. Anomalies of bottom surfaces, such as microtrenching and roughness (or residue), affect the uniformity of bottom surfaces and lead to the

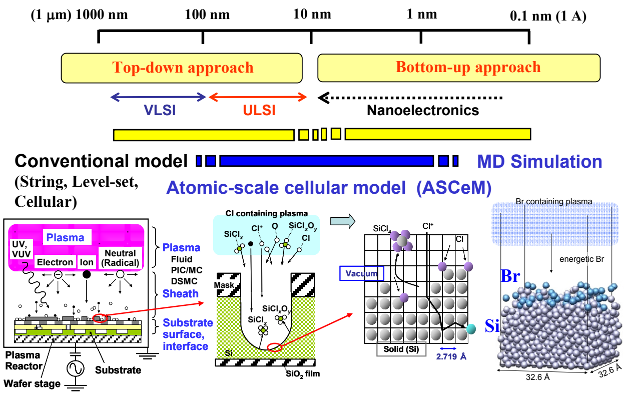

Fig.1. Modeling and simulation of plasma-surface interactions in materials nanofabrication.

recess and damage in gate fabrication.

Moreover, new materials are also being required to be precisely etched in integrating them into device fabrication [3−5]. In FEOL, recent efforts have been made to replace gate silicon-oxides and -oxynitrides by high dielectric constant (*k*>20) materials such as HfO_2, ZrO_2, and their silicates and aluminates, where highly selective etching of high-*k* over underlying Si is indispensable for their removal prior to forming source and drain contacts. For the fabrication of high-*k* gate stacks, gate electrodes of conventional poly-Si are being required to be replaced by metal gates such as TiN, TaN, Ru, Pt, and Ir, to suppress some problem of the depletion layer present in doped poly-Si. Chlorine- and bromine-based plasmas are also often employed in etching of these high-*k* and metal electrode materials.

In these situations, the modeling and simulation of plasma-surface interactions is required for a better understanding of the physics and chemistry underlying the phenomena observed, as well as for a theoretical design of plasma reactors and processes with less experimental efforts [5,6]. The model is divided in four areas or categories: a plasma reactor or equipment model (including the sheath region on reactor chamber walls and substrates), model for plasma-surface interactions for blanket substrate surfaces and chamber walls, model for plasma-surface interactions for small feature surfaces (model for profile or topological evolutions), and model for electrical characteristics and damages of substrate materials and interfaces. A Monte Carlo-based atomic-scale cellular model (ASCeM) is available to simulate the feature profile evolution on nanometer scale during processing, and a classical molecular dynamics (MD) simulation is also available to clarify the profile evolution as well as surface reaction kinetics on atomic scale, as shown in Fig, 1.

3. Space Propulsion

Small spacecraft has recently attracted increasing attention in space technology to reduce the overall mission costs and increase the launch rates, which in turn requires miniature or micro thrusters including micro electric propulsion systems or micro plasma/ion thrusters [7,8]: DC current microarcjet thruster, DC microplasma thruster, microwave-excited microplasma thruster as shown in Fig. 2, micro Hall thruster, micro ion thruster, and dielectric capillary discharge acceleration using gas fuels; field emission electric propulsion and colloid thruster using liquid fuels; vacuum arc microthruster, micro laser-ablation plasma thruster, micro pulsed plasma thruster, and ferroelectric plasma thruster using solid fuels. In these systems, the surface-to-volume ratio of microplasma sources is relatively high, and so the particle and energy loss to chamber walls is severe, thus resulting in significant plasma-surface interactions to erode the chamber walls. The erosion is most significant at around the end of the antenna in Fig. 2, where the plasma density is calculated to be high. The numerical model consists of an electromagnetic module for microwave propagation in interacting with plasmas and a fluid module for plasma flows with two (electron and heavy particle) temperatures.

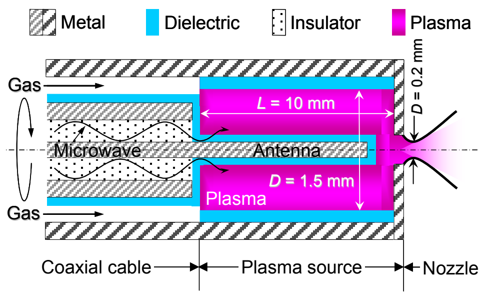

Fig.2. Microwave-excited microplasma thruster of electrothermal type.

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