Plasma Etching

An Introduction

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3 An Introduction to Plasma Physics for Materials Processing

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I. Introduction

The processing of materials by plasmas requires detailed knowledge in several scientific and technological areas. This is particularly true in the field of semiconductor fabrication where the continuing development of denser arrays with finer features has demanded the combination of various techniques into a highly specialized art. Perhaps the basic foundation for this art is plasma physics, though chemistry, electrical engineering, and vacuum technology have defensible claims. Each must be understood and well-practiced for the material processing to succeed.

In this chapter we will present the fundamental concepts in plasma physics which underlie the operation of plasma processing equipment. This will include discussions of the types of particles present in processing plasmas, their energies and fluxes, and an elucidation of the characteristic lengths, time scales, excitable modes (both stable and unstable), and atomic and surface processes important in the initiation and maintenance of plasma discharges. To discuss these topics in a practical way, we include information from a wide range of plasma configurations used in plasma processing, presenting material on dc- and rf-driven discharges with and without externally applied magnetic fields.

The understanding of plasmas that are unmagnetized, isothermal, isobaric, and isotropic is already rather difficult. The configurations used in all processing devices do not have even this simplicity, in large part due to the boundary between the plasma and the solid surfaces. It is at the boundary that our ultimate interests lie. However, the reader should find that the simplified situations described here will form a good understanding of the often counter-intuitive behavior of plasmas and will encourage improvements in existing equipment or processes.

Plasmas are usually created in metal vacuum vessels, commonly used to attain the low pressures essential for particular plasma properties. Plasmas have a propensity to fill every crevice in these vacuum vessels. (The word "plasma" originates from a Greek root meaning deformable.) And though efforts are made to constrain the plasma to particular sections of the vessel, these are not completely successful. Device operation is considerably affected. To emphasize this, we shall use the label "containment" vessels to fully appreciate that some plasma reaches everywhere in them.

We assume familiarity with college physics (especially Maxwell's equations) and introductory calculus. Most equations will be presented both in cgs and practical units to aid their easy application. Section II presents most of the basic ideas and definitions concerning plasmas. These are developed in the later sections. Section III concerns single-particle motion;

Section IV gives details of plasma parameters; Section V is devoted to plasma formation; and Section VI applies the previous four sections to the magnetron device.

II. The Plasma State

Plasmas are a state of matter that consists of a large group of electrons and ions with nearly equal numbers of opposite charges, each particle moving at a high rate of speed relative to the others. It is the precise electric field of the individual charged particles that gives the plasma its unique properties. The electric field of each particle influences the motion of distant particles, whether they have like or opposite charge. This action-at-a-distance causes a wide variety of waves and instabilities to be possible in a plasma. And because each particle is influenced by the electric and magnetic fields of many particles, the term used to describe the kinematics is *collective motion*.

The electric field of a single isolated electron is proportional to r^{-2}. The volume of a spherical shell a distance r from that electron increases proportional to r^2. Thus, the product of the electric field times the volume, a measure of the effectiveness of the field at a distance, is constant (Fig. 1a). It is the same near the electron as it is far away, showing how the action-at-a-distance arises.

What differentiates a plasma from a group of neutral atoms that also has equal and large numbers of electrons and ions? It is the distance at which the electric field is felt strongly. Neutral atoms (and molecules) have an electric field no stronger than a dipole. This falls-off proportional to the distance cubed or faster. Hence at large distances, it is weak compared to the Coulomb electric field of the bare electrons found in a plasma. Because of the very short range of their electric and magnetic fields, molecules interact with each other only by "hard" collisions, meaning close encounters, typically at separations of about 1 Å. Free electrons and ions in a plasma interact over much greater distances, typically 1000 Å or more, as well as less, of course!

Numerous distant interactions will change a charged particle's trajectory more than the infrequent hard collisions (Fig. 1b). For this reason close encounters may be unimportant to the charged particles in a plasma. (This is related to another reason why a group of neutral atoms does not behave like a plasma. The quantal nature of the electronic energy levels in an atom precludes the small changes in energy required by distant encounters so important to plasma behavior.) Hence plasmas are frequently termed *colli-*

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