Design of High-Density Plasma Sources for Materials Processing

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ISBN 0-12-533018-9

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I. Introduction

The advent of sub-micron electronic device fabrication has brought unprecedented demands for process optimization and control (*1*,*2*) which, in turn, have led to improved plasma reactors for the etching and deposition of thin films. As a result, we have witnessed the introduction of a new generation of plasma systems based on electron cyclotron resonance (ECR) heating (*3–6*). ECR plasma etching of polycrystalline Si, single crystalline Si, silicides, Al, Mo, W, SiO_2, polymers, and III–V compound semiconductors have all been reported in recent years (*7–33*). Similarly, ECR plasmas have been used to deposit amorphous Si, silicon nitride, boron carbide, and SiO_2, to name just a few materials (*34–40*). Applications of ECR plasmas beyond etching and deposition have also been reported and include ion implantation (*41–45*), surface cleaning (*46–59*), surface passivation (*60*), and oxidation (*53*,*61–63*). Besides ECR, many other "novel" plasma generation schemes are now being offered to satisfy manufacturers' needs in these materials processing areas. All these schemes purport to offer advantages over conventional approaches such as the capacitively coupled radio frequency discharge now used in many factories for etching and deposition of thin films during integrated circuit manufacturing.

But which scheme is best? What are the key aspects to plasma source design that affect materials processing? And why are the conventional approaches inadequate? While the answers to these questions remain elusive and are the subject of much current research, one can clearly identify commonalities and differences between the novel sources, whose most distinctive characteristic is higher efficiency than their conventional counterparts operated at low pressure. The purpose of this review is to (1) develop a unified framework from which all "high-efficiency" sources may be viewed and compared; (2) outline key elements of source design that affect processing results; and (3) highlight areas where additional research and development is needed. In so doing, we hope to assist those who use plasma for materials processing to make wise choices in constructing or purchasing sources, to guide vendors of high-efficiency sources in choosing designs that can best meet their customers' expectations, and to inspire the research community to focus on problems of technological interest.

Before such a review can be begun, several disclaimers must be made. First, the literature on applications, diagnostics, and modeling of high-efficiency sources is now so voluminous that we are not able to review or reference every paper. Rather, we have opted for highlighting key results in line with our objectives stated earlier. Second, we restrict our focus to those aspects of plasma processing that are uniquely affected by the use of high-efficiency plasmas. For example, we discuss aspects of source design that affect plasma-induced electrical damage in microelectronic circuits, but a comprehensive discussion of damage mechanisms is the subject of its own review and clearly beyond the scope of this work. Third, there are pertinent areas that while important are not yet ready for review. Foremost amongst these is the field of numerical simulation. While impressive results have been reported recently and we will draw on some of these, little has appeared in print and it is premature to review the field. Similarly, the stability of high-efficiency sources is a matter of some concern, and recent work illustrates that sudden mode changes and bistability may adversely affect materials properties, but too little has been reported and analyzed to make a thorough discussion meaningful. Finally, any review reflects the biases of the authors, and this work is no exception. Based on our interests and experience, we focus on applications of plasmas to microelectronics fabrication and, in particular, etching. Heavy emphasis is placed on simple, analytical, unifying theories and quantitative diagnostic measurements.

Why new sources? In plasma etching, the shrinking dimensions of micro-electronic devices have placed unprecedented demands on process control. Consider critical dimension (CD) control where the width of the transistor gate is specified to better than 10%. For yesterday's CD of 1 μm, this means a linewidth variation of 0.1 μm can be tolerated, but by the end of the 20th century when the CD should be only 0.25 μm, variations in CD must be less than 0.025 μm. This requires unprecedented anisotropy in the plasma etching of gate electrodes, contact windows, and metallic interconnections. To achieve such control, we need to increase the anisotropy of ion transport to the device wafer from what it is in the conventional capacitively coupled rf reactor. This means operating plasmas at lower pressures. But conventional rf sources are inefficient at low pressure, so that high powers must be used to achieve the high rates of ionization and dissociation necessary for high-throughput, low-cost manufacturing. Unfortunately, excessive power input to a capacitively coupled system leads to high ion bombarding energies that can degrade selectivity in etching and produce electrical damage that reduces device yield. Thus, new sources are needed to operate at lower pressure and higher efficiency.

In conventional rf systems, ion energy and flux are inexorably linked. But ion energy control is needed in plasma deposition to tailor film properties such as stress, composition, refractive index, crystallinity, and topography. Ion energy control is used in plasma etching to optimize selectivity and minimize atomic displacement damage while meeting linewidth and throughput specifications. Therefore, gaining superior control of ion energy and decoupling it from ion flux control is further motivation for developing new plasma sources and processing systems.

In the remainder of this section, we review briefly the properties of capacitively coupled radio frequency plasmas and elaborate further on the advantages of high-efficiency sources. In the following sections, we first discuss the fundamental principles underlying high-efficiency plasma source design and, to compare one source with another, use a simple analysis in Section II that allows estimation of electron temperature, ion bombardment energy, and plasma density in terms of the gas phase cross-sections, gas density, absorbed power, and source dimensions. In this way, we provide an approximate but common framework with which one source can be compared to another. In Sections III–VII we discuss in greater detail ECR, helicon, inductive, helical resonator, and surface wave sources, respectively. Emphasis is placed on electron heating and power absorption, since these are the primary differences between one source and another. In Section VIII, we turn to the issue of plasma transport and independent control of ion energy and flux.

Obtaining such control is largely independent of the electron heating mechanism but depends critically on source design parameters such as the magnetic field and power absorption profiles. We focus our attention in Section VIII on measurements of ion energy distributions, mostly in ECR systems since few data are available from other systems. In Sections VIII and IX, we relate ion energy and plasma uniformity, dictated by source design, to processing results such as etching anisotropy, atomic displacement damage, and charge-induced damage. In the final section, we highlight remaining issues and the areas where further investigation is needed.

Throughout this paper we strive to be consistent with dimensional analysis despite not using a consistent set of units. Generally, magnetic field is expressed in gauss, distances in meters, centimeters, or millimeters, and the electron charge in coulombs. Energies are usually given in units of volts, not electron volts, so the value of e is explicitly written. Pressures are given in Torr or milli-Torr. While this does not conform to international convention, it does conform to common usage. We apologize to the purists.

A. CAPACITIVELY COUPLED RADIO FREQUENCY DISCHARGE SOURCES

Capacitively driven rf discharges—so-called rf diodes—are the most common sources used for materials processing. An idealized source in plane parallel geometry, shown in Fig. 1a, consists of a discharge chamber containing two electrodes separated by a spacing l and driven by an rf power source. The substrates are placed on one electrode, feedstock gases are admitted to flow through the discharge, and effluent gases are removed by the vacuum pump. Coaxial discharge geometries, such as the "hexode" shown in Fig. 1b, are also in widespread use. When operated at low pressure, with the wafer mounted on the powered electrode, and used to remove substrate material, such reactors are commonly called reactive ion etchers (RIEs)—a misnomer, since the etching is generally a chemical process enhanced by energetic ion bombardment of the substrate, rather than a removal process due to reactive ions. When operated at higher pressure with the wafer mounted on the grounded electrode, such reactors are commonly referred to as plasma etchers. In terms of the physical properties of these systems, this distinction is somewhat arbitrary.

The physical operation of capacitively driven discharges is reasonably well understood. As shown in Fig. 2 for a symmetrically driven discharge

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