Uniformity Control with Phase-Locked RF Source on a High Density Plasma System

David J. Coumou, Dennis M. Brown
MKS Instruments Inc., ENI Products

Abstract

Semiconductor device manufacturing continues to achieve decreased feature sizes with a corresponding density increase along device area and volume. The consequence of manufacturing semiconductor devices with a higher level of integration remains a vexing challenge to achieving repeatable target yields, minimizing plasma induced damage, and optimizing process throughput all while gaining the technological advantage to reach the next high-performance node. We present control mechanisms to improve the fidelity of plasma density and the control of ion energies for a high-density plasma source. For a high-density plasma (HDP) source, plasma generation is associated with the coupling of RF power to the plasma discharge through a coil antenna arrangement. The RF bias, coupled to a substrate, creates the ion energies utilized for material etch processing associated with high-volume semiconductor manufacturing. Our fundamental technique is based on a frequency-and-phase locking controller. For the RF source, this frequency-and phase locking enables precise control of the electromagnetic field emissions from the antenna. By amplitude and relative phase manipulation of a dual-RF power supply scheme providing the excitation for the source antenna, the constructive-deconstructive interaction of the coil fields enables the finest control of plasma density and uniformity along the wafer area. We further exploit the frequency-and-phase locking capability with the bias RF power delivery system to control the width and skew of the ion energy distribution function (IEDF). The coupling of these RF power delivery systems to a high-density plasma source formulates a systematic control of plasma parameters, ameliorating the state of thin-film manufacturing capability closer to the elusive atomic layer etch facility necessary to achieve future semiconductor nodes.

Index Terms - Automatic control, digital control, frequency locked loops, IEDF, phase frequency detector, phase locked loops, plasmas, plasma density, plasma properties, plasma sheaths, radio frequency, real-time systems, RF Signals

Introduction

A semiconductor fabrication facility uses plasma systems and other semiconductor manufacturing tools [2] for deposition with subsequent etch processes to fabricate devices for the construction of integrated circuits. As manufacturers of consumer electronics continue to commoditize user capabilities ubiquitously in low cost devices, the density of integrated circuits becomes critical, commensurate with the plasma systems used in their fabrication. RF power delivery systems are the principal sub-systems in the plasma processing reactors used for volume thin-film manufacturing [1]. The deposition of dielectric and insulating films uses RF power for Plasma Enhanced Chemical Vapor Deposition (PECVD). These tools control film qualities within Angstroms. Capacitively coupled plasma systems are used to etch these films. High-density plasma tools comprise of inductively coupled plasma (ICP) reactors, and these are widely used to etch conductive and polysilicon material. Deposition tools have led with advanced capabilities, however etch tools lag in comparison [3]. To address this specific challenge, we present a set of non-intrusive RF power delivery systems for inductively coupled plasma systems. By employing a frequency-phase locking (FPL) digital controller, the relative phase between a dual-frequency RF power delivery system is controlled. We devise a method from this capability to control the plasma density and uniformity on an ICP, and extend the digital FPL controller to generate a harmonically-related RF power delivery system for the ICP bias. The combination of these RF power delivery systems provides the tool user with the highest degree of plasma parameter controllability utilizing the existing RF infrastructure on conventional plasma systems that are used in semiconductor manufacturing environment today.

In the next section, we provide a short overview of schemes used for ICP source control for the purpose of plasma density and uniformity. We then present our simulation results using our system and describe our RF power delivery system to revolutionize the capability of high-density plasma systems. For conciseness and brevity of this narrative, we do not present the FPL digital controller. The interested reader is directed to [4]-[6] for a descriptive analysis and utility.

Plasma Density and Uniformity Control

Plasma generation in an ICP reactor occurs by coupling RF power through an antenna scheme, with the conventional approach using a dual coil arrangement. The coil arrangement consists of a planar set of coils, designated as inner and outer. Resting upon a dielectric window in atmosphere, the coils are excited by an RF source to generate plasma on the vacuum side of the dielectric. The density of the plasma is controlled by the field intensity from the coil arrangement. By adjusting the current through coil arrangement, the EM fields can be manipulated in such a way as to control the emitting field intensity and its uniformity. By doing so, the amount of plasma and the location of the plasma source are controlled. Industry has adopted a number of schemes to accomplish plasma density and uniformity control, albeit with varying degrees of complexity and effectiveness.

By pulsing the RF power supply system exciting the ICP source, plasma uniformity has been demonstrated [7]. The concept is to pulse the source coils after a steady-state plasma is achieved in continuous RF mode. From a HPEM3D simulation, the evolution of plasma density sequentially achieves uniformity after a few pulses from a 10 KHz, 50% duty cycle pulse-train.

Consequently, source pulsing in the absence of a bias RF power is a challenge due to the difficulty of obtaining stable plasma through repetitive transitions from a vacuum state to a plasma state. By influencing the source in a time-averaged manner, other plasma parameters are impinged [8]. This scheme is primarily related to asymmetric vacuum pumping schemes. High density plasma sources more commonly use symmetric vacuum pumps, and as a result, this is a narrow solution with limited applicability for conventional HDP systems.

By adjusting the current ratio to the source coil pair, the relative phase of the excitation provides a mechanism of varying field intensity to achieve uniform field strength. Simulation results are shown in [9] for its effectiveness to control plasma uniformity. Ratio control is generally accomplished with a variable reactive element in the impedance matching network, located between the RF power supply and the antenna [10]. The variability of the reactance provides limited phase variation to the fields. In contrast, the proposed scheme that we describe next, achieves independent and closed-loop field intensity (power set point) and field uniformity (±π phase relationship) control.

Frequency and Phase-Locked RF for Field Uniformity

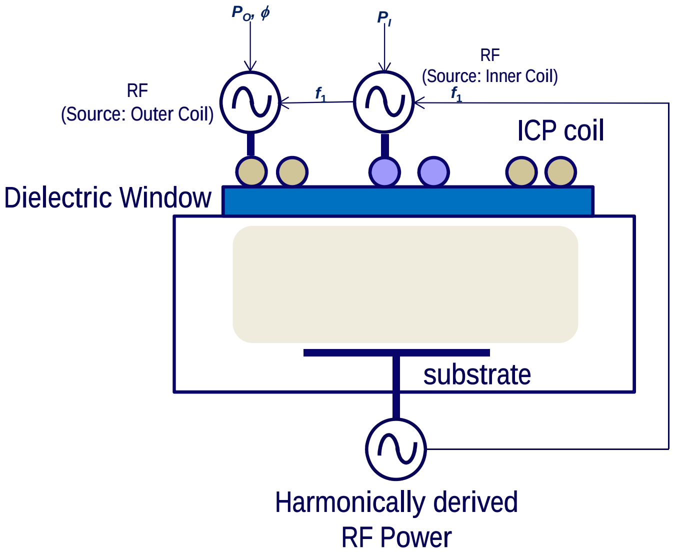
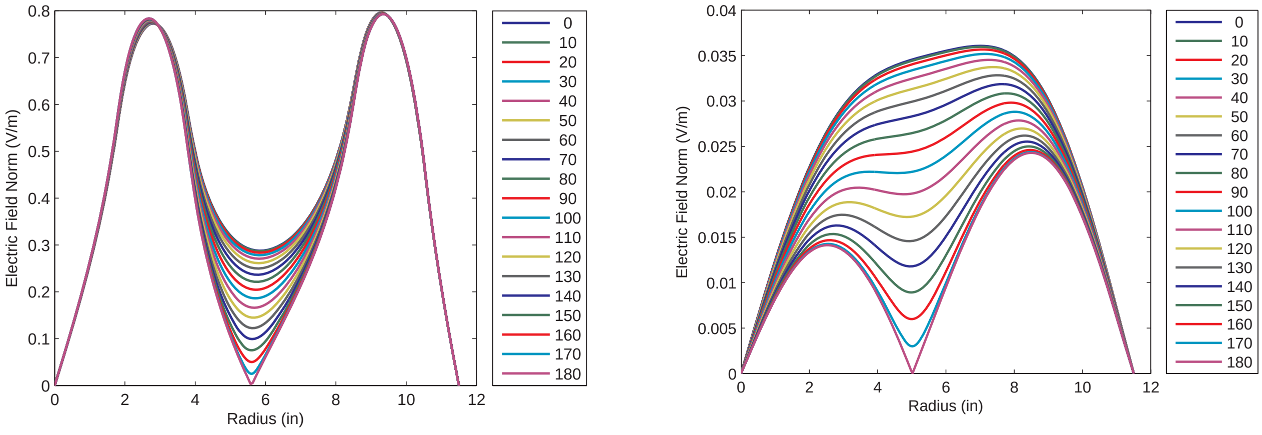


Figure 1: High Density Plasma Source with independent plasma density control and IEDF control

The proposed high-density plasma system is schematically shown in Figure 1. The top side of the reactor is the ICP coil set above the dielectric window. The coil set comprises an inner (purple fill) and outer (light brown fill) coil. The inner coil is shown as a single-turn arrangement and the outer coil is configured with two-turns. Each coil is powered by an RF power delivery system consisting of an RF generator and associated impedance matching network. The power supplies designated for the inner and outer coil share an excitation signal to translate the operating frequency of one power supply with the second. In this case, the outer coil is slave to the inner RF power delivery system. In this arrangement, the coil frequencies are the same (frequency locked). The power supplies for the coils are configured with power set points for the inner (P_I) and outer (P_O). These settings are selected to couple RF power for a desired plasma density and uniformity along the substrate area. The ratio of P_I and P_O yields a particular EM field intensity to generate a roughly uniform plasma density. The relative phase of the source RF power supplies is configured by ϕ. For control of the sheath modulation function, we show an excitation signal connected from the bias RF power delivery system to the master source, in this case, the inner coil. In principle, the slave source RF power supply(ies) can be harmonically derived from the master source RF power supply or from the corresponding frequency from the harmonically driven bias.

The phase parameter for the source RF power delivery system provides a control variable to generate unique EM field profiles, which corresponds to plasma density and its corresponding uniformity. With adjusting phase, the coil fields interact in a constructive to destructive manner as a periodic function of the phase. This is illustrated in the plots shown in Figure 2 for the electric field generated for coils excited at the same frequency along the surface of the atmospheric side of the dielectric window and 3.5 inches below the dielectric in the reactor's vacuum. The ratio of the outer voltage to the inner coil voltage is 3.4. The variation of the field strength clearly shows a relationship with phase.



(a)

(b)

Figure 2: Electric field strength from the coil set along the radius from the center of the coil arrangement as a function of phase, ϕ, in Degrees; (a) along the dielectric surface; (b) below the dielectric window at 3.5 in

With the applied voltage out of phase (180 Deg.), the field strength slightly above the substrate produces two distinct peaks. The magnitude of the field strength increases and achieves uniformity for $|\phi| < 90$. The control of the field intensity and uniformity provides direct control of the plasma density and its uniformity.

By connecting the source RF power delivery system with the bias RF power delivery system, we achieve a control solution for unique plasma density and IEDF generation. These can be coordinated in time-varying control of independent plasma generation and IEDF for a greater fidelity of ionization and dissociation. For instance, the power and phase of the source RF power delivery system is synchronized with the bias RF, enabling plasma generation in-phase or offset with the harmonic frequency-phase controlled IEDF.

We note the scalability of our scheme for source excitation. As the number of coils comprising the set increases, RF power supplies are added for each coil with the excitation signal mutually shared for a common power supply frequency with phase control, ϕ, assigned to each RF power supply. In summary, the source coils have multiple slaves derived from one source master with each slave a configurable phase, ϕ.

Conclusion

We presented a scheme to regulate EM fields for the coil arrangement on an inductively coupled plasma source with continuous phase control for a multiple RF power delivery system. By time-varying control of the source EM field intensity and uniformity, a control mechanism is introduced for the generation of ion density commensurate with IEDF control from the bias. Our framework embraces the pathway established with multiple RF power delivery systems and has a scalable architecture for adaption to expanded coil sets (e.g., 450 mm). We achieve total plasma parameter (density, electron temperature, potential, etc.) control on a high-density plasma source. The source, governing plasma density production, is controlled with phase-frequency of the coil set, and the bias controlling the IEDF with harmonic frequency-phase control for the remaining plasma parameter quantities.

References

1. Lieberman, M. A. and Lichtenberg, A. J., in *Principles of Plasma Discharges and Materials Processing*, John Wiley and Sons, New York, 1994.
2. Geng, H.; *Semiconductor Manufacturing Handbook*; McGraw-Hill, New York, 2005
3. Gottscho, R. A.; “Plasma Etching - The Challenges Ahead in Enabling Nanoelectronics”; *Proc. of the 64th Annual Gaseous Electronics Conference*, Vol. 56, No. 15, 2011
4. Coumou, D. J.; “Phase and frequency control of a radio frequency generator from an external source”; US Patent No: 7,602,127, Oct. 2009

5. Clark, D. H.;Coumou, D. J.; Shannon, S.; "IEDF Control using Multifrequency Harmonic Drive"; *Proc. IEEE Plasma Science* (ICOPS); 2012, p. 2
6. Coumou, D. J.; Clark, D.H.; Kummerer, T.; Hopkins, M.; Sullivan, D.; Shannon, S.; "Ion Energy Distribution Skew Control Using Phase Locked Harmonic RF Bias Drive"; *IEEE Trans. Plasma Sci.*, Submitted Sept. 2013, pending IEEE publishing.
7. Subramonium, P.; Kushner, M. J.; "Pulsed inductively coupled plasmas as a method to recoup uniformity: 3D Modelling Study"; *APS Letter*, Vol. 85, No. 5, Aug 2004, p. 721-723
8. Banna, S.; Agarwal, A.; Cunge, G.; Darnon, M.; Pargon, E.; Joubert, O.; "Pulsed high-density plasmas for advanced dry etching processes", *J. Vac. Sci. Technol. A*, **30**, 040801 (2012).
9. Agarwal, A.; Banna, S.; Todorow, V.; Rauf, S.; Collins, K.; "Impact of Phase Shifted Coil Currents on Plasma Uniformity"; *IEEE Trans. on Plasma Science,* Vol. 39, No. 11, p. 2516-2517, Nov. 2011
10. US Patent Application 2011/0097901, April, 2011

MKS Instruments
2 Tech Drive
Suite 201
Andover, Massachusetts 01810
USA