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著者	大見　忠弘
journal or publication title	IEEE Transactions on Semiconductor Manufacturing
volume	6
number	1
page range	58-64
year	1993
URL	http://hdl.handle.net/10097/48006

doi: 10.1109/66.210658

Independent Control of Ion Density and Ion Bombardment Energy in a Dual RF Excitation Plasma

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Abstract—**A dual RF excited discharge is described. The dual RF excitation system provides a method to control the substrate self-bias without affecting the state of the discharge. The substrate can be RF-biased utilizing an appropriate excitation frequency and power significantly less than the plasma generating RF power. The substrate self-bias dependence on various system parameters including substrate excitation frequency, pressure, plasma generating upper electrode RF power, substrate material and process gas compositions are described. For a simplified model, a linear relationship between self-bias and RF power is derived using the space-charge limited assumption. The effect of substrate bias on the thermal-oxide etch rate has been studied. The results show good correlation between the ion bombardment energy, i.e., the potential difference across the substrate dark space, and the SiO_2 etch rate. The SiO_2 etch rate in a CF_4 plasma increases linearly with the ion bombardment energy having a threshold etch energy of ~ 19 V.**

I. Introduction

During the past decade there has been rapid development in the field of plasma processing technology in the semiconductor industry [1]–[4]. Among applications [5], plasma etching requires a low pressure radio frequency (RF) discharge of halogenated gases. In reactive ion etching (RIE), charged ions accelerated by the DC sheath potential strike the unmasked surface of thin films to produce volatile materials. The role of positive ions are: 1) transfer of reactive species; 2) provide kinetic energy required at etched surface and 3) provide directionality required to achieve the accurate transfer of submicron patterns.

Since conventional RIE systems utilize a single RF source for both plasma generating and substrate biasing purposes, an independent control of the radical species production and the ion bombardment energy can not be achieved. Recently, the use of a microwave discharge [6] and other means [7], [8] of producing high-density discharges are becoming more popular. However, since the uniformity and directionality of charged particles are strongly affected by magnetic field, the systems utilize strong magnetic field may not be suitable for producing an uniform plasma over large diameter substrate. There have been several other research works [9] that utilize a dual RF excitation plasma configuration with two commercial RF sources (13.56 MHz, 100 kHz, etc.) to separate the plasma generating RF source from the substrate RF-biasing source.

A four fold increase in device integration every three years substantially has reduced chip dimensions following scaling theory [10]. Since the increase in current density defined by the scaling theory is known to rapidly increase electromigration failure, interconnections will become the limit in performance and reliability of future devices [11], [12]. Although the problems of electromigration and hillocks preclude using aluminum interconnections, it has been reported that hillock-free aluminum films can be obtained by simultaneous bombardment of the growing film with low energy argon ions [13]. In this [13] work, the potential of the substrate wafer was dc-biased to determine the effect of ion bombardment energy on the film quality. For a potential difference between plasma and substrate of 50 V or greater, the bombardment energy of Ar ions, hillock-free aluminum files were achieved. The effect of low kinetic energy ion bombardment of the substrate surface has been also confirmed for a sputtering silicon epitaxial process at extremely low temperatures such as 300°C [14].

In the fabrication of DRAM cells, scaling theory has also revealed a major concern associated with the charge storing capacitor. The signal charge stored across a capacitor which has an area A and an insulator with a thickness t and dielectric constant ϵ is given by

$$Qs = A \cdot \epsilon \cdot V/t. \tag{1}$$

As shown by this simple relationship, if the characteristic dimension is decreased by one-half, the oxide thickness must be reduced to one-fourth of its original thickness for the same dielectric. The oxide thickness used for one transistor DRAM storage capacitors is < 10 nm for the currently developed DRAMs [15], [16]. Two obvious problems in implementing the above hillock-free process on such extremely thin oxide films are as follows:

1. We can no longer dc-bias the film being deposited. Thus, the first few layers of the deposited film may suffer imperfections.
2. If the oxide films are exposed to high energy ions, the quality of the thin oxide can be significantly degraded

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Manuscript received January 28, 1990; revised November 25, 1991.

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IEEE Log Number 9205041.

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by radiation damage during the deposition process or subsequent lithography process for interconnections. In order to successfully realize low kinetic energy hillock-free sputter deposition without resulting in deleterious effects on thin oxide layers, the ion bombardment energy must be substantially reduced and accurately controlled [17].

In this paper, a method is presented to accurately set the substrate potential and independently control the ion bombardment energy and flux density using a dual RF excitation plasma configuration.

II. Experimental Setup

The schematic diagram of the experimental system is shown in Fig. 1. The system consists of a cylindrical stainless steel discharge chamber 400 mm in diameter and an oil-free vacuum system consists of a magnetically coupled Turbo Molecular Pump (Seiko H-1000) and dry pump (Drystar CDP-80). To study the effect of ion bombardment energy on the thermal oxide etch rate, CF_4 was used as the reactive gas in addition to Ar. A mass flow controller (STEC-400) was used to regulate the operating pressure by controlling the total process gas flow into the chamber. In the RIE study, a 4-inch silicon wafer was electrostatically chucked to the upper plasma generating electrode to prevent contamination from sputtering of the electrode material and clamps. A 4-inch patterned sample wafer was placed on the lower substrate electrode for etching. Throughout the experiments, a set of water cooled multi-pole magnets placed in the upper electrode provided a stationary maximum magnetic field of 500 gauss 15–20 mm from the axial center. The magnetic field intensity at the substrate electrode, 30 mm from the upper electrode surface, was 50 gauss. The potential distribution of the plasma was measured using a Langmuir probe inserted in the horizontal direction through the vacuum sealed flange. The description and method of probe measurements are more fully discussed elsewhere [18]. An optical multichannel analyzer was employed to monitor plasma effluents through an optical polished quartz window to determine the effects of pressure.

The thermal oxide samples used in the etch rate study were grown in a H_2/O_2 environment of 20 slm each, at 1125°C. A photoresist (OFPR-800) pattern with approximately 70% oxide exposure was used as the mask. Etched depths were measured with a surface texture analysis system (DEKTAK 3030ST). Dual RF excitation

When a second RF signal is applied to the conventionally non-powered electrode, does it influence the electrical field of the primary RF? Consider the impact of hardware configuration on the RF path and how to achieve so called "independent" control of radical species production and substrate bombardment ion energy.

It has been suggested that in order to electrically separate a non-powered electrode from a powered electrode, the non-powered electrode must be properly RF-ground with an appropriate band-pass-filter [19]. In practice, however, it is found that effectively RF-grounding the electrode for the particular RF frequency can be quite difficult. The difficulties arise because the quality factors (Q) of commercial band-pass-filters are not high enough and the dark space capacitance varies with plasma conditions, wafer size, etc. Hence no band-pass-filter is used in this study.

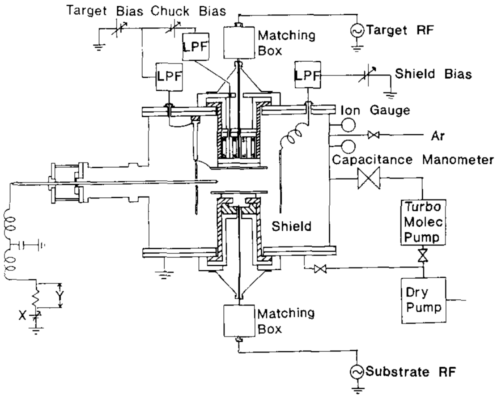

Fig. 1. Schematic diagram of dual excitation plasma system.

The simplified circuit of the experimental system is shown in Fig. 2. The residual inductance between the electrode and ground can be ignored for the excitation frequency of that particular electrode since it becomes a part of the matching network. However, L_1 and L_2 become the significant elements in isolating the RF power of the opposing electrode, RF_2 and RF_1, respectively.

The effects of L_1 and L_2 were determined by measuring the RF impedance between electrodes and ground using a network analyzer. With the driving frequency of 100 MHz RF applied to the upper electrode, the impedance of matching network 2 in series with L_2, measured from the plasma including the 50 Ω cable and the power unit, is $-j15.7$ Ω (tuned at RF_2 of 30 MHz). Since L_1 and L_2 are 0.21 μH, the total impedance between the substrate holder and ground for RF at 100 MHz is $+j116$ Ω. Instead of conducting a detailed analysis of the plasma impedance, this value was compared with the stray impedance between the electrodes and walls. Since the previous study [18] showed that the plasma impedance is always capacitive for the conditions we operate in and that stray capacitance exists in parallel with the plasma impedance, the total capacitance between the electrode and walls is larger than the stray capacitance. Thus, if we can ignore the resistive component of the plasma, the combined RF impedance is smaller than the impedance calculated for the stray capacitance alone. The stray capacitance measured using a network analyzer was 31.8×10^{-12} F or an equivalent impedance of $-j50.5$ Ω at 100 MHz.

Since the RF impedance between the substrate (non-powered) electrode and ground is significantly higher than the impedance between the upper (powered) electrode and walls, only a fraction of the RF current is transmitted through the substrate electrode and the rest terminates to the grounded walls. Similar measurements for the upper

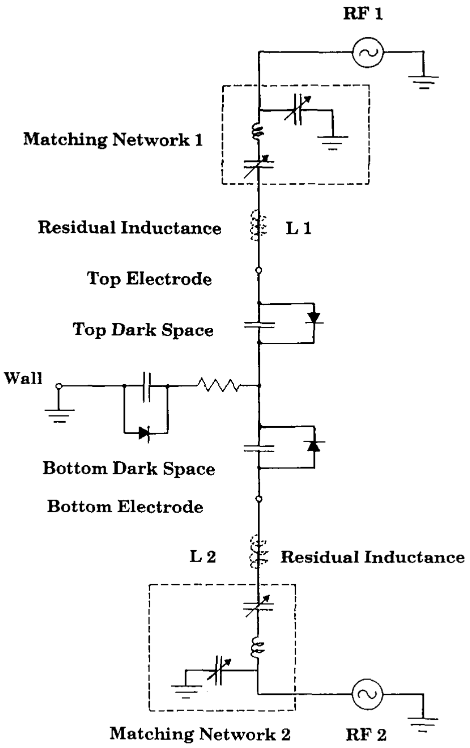

Fig. 2. Electrical model for experimental system.

electrode show the RF impedance between the upper electrode and ground to be 734 Ω for RF_2 at 30 MHz (RF_2), which is again much higher than the stray impedance. Consequently, we can reasonably state that for the system used in this study each electrode has a high impedance to ground at the frequency of the opposing electrode so as to not pass RF current and cause rectification.

III. Results and Discussion

A. Substrate RF-biasing

The dual RF excitation plasma process can be categorized into two main modes, i.e., "sputtering" and "RIE". In both cases, the plasma density is controlled by the RF power of the upper electrode which is the plasma generating electrode. Also, the substrate potential is determined by varying the power and frequency of the substrate RF. Note, however, that in order to achieve independent control of the ion bombardment energy and the ion density, the substrate RF power should be substantially smaller than the plasma generating RF power.

In Fig. 3, the control of the substrate self-bias is shown for various substrate frequencies. It can be seen that the substrate dc potential can be varied without influencing the target self-bias voltage. The proper selection of the substrate biasing RF is also extremely important because an accurate control of the bombarding energy at low energy regimes (< 50 V) can not be obtained when the excitation frequency is too low. This is because ions begin to follow the ac electric field at low excitation frequency, and the ion energy distribution starts to widen below the threshold frequency [20]:

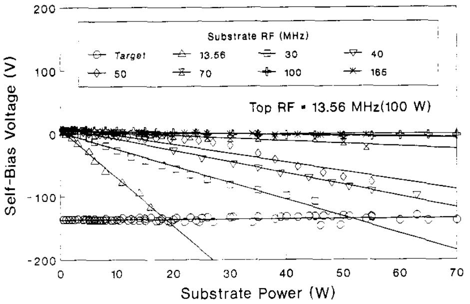

Fig. 3. Substrate self-bias dependence on frequency and power of substrate RF. Plasma is generated by upper electrode RF of 13.56 MHz (100 W). Argon pressure is 7 mTorr.

$$\omega = (n_e \cdot e^2/m_e \epsilon_0)^{0.5}. \tag{2}$$

For an argon plasma of 7 mTorr and n_e of 1×10^{16} m^{-3}, the threshold frequency is 3.3 MHz, which is in a good agreement with reported values [21].

The effects of varying the process pressure in low pressure regimes (5 ~ 40 mTorr) are shown in Fig. 4. The data shows representative voltage distributions in the RIE mode in which the top electrode is biased with extremely high RF (100 MHz) while the substrate is biased with relatively low RF (13.56 MHz). The results showed constant self-bias dependency on the substrate RF power up to 30 W. In single RF excited systems, in general, the self-bias of a powered electrode decreases with an increase in pressure, as shown in Fig. 5. This is due to the proportional increase in ionization efficiency at higher pressure as observed by the corresponding increase in Ar (419.9 nm) emission intensity. From Bohm's criterion for ion sheath formation and the Child–Langmuir equation, the sheath thickness can be expressed as follows [22]:

$$d^2 = \epsilon_0 (V_p - V_{dc})^{1.5} / n_e (e \cdot \kappa T_e)^{0.5} \tag{3}$$

Where V_p is the time averaged plasma potential, V_{dc} is the electrode self-bias voltage and n_e and T_e are the plasma density and electron temperature respectively.

Hence, the sheath thickness depends not only on the sheath potential difference but also inversely depends on $n_e^{0.5}$ and $Te^{0.25}$. When the product of $n_e^{0.5}$ and $Te^{0.25}$ increases with pressure, the sheath thickness becomes smaller and sheath capacitance increases. An increase in sheath capacitance results in smaller voltage division between cathode and anode sheaths and smaller cathode self-biased voltage.

In a dual excitation system, the plasma is primarily generated by the upper electrode RF field and the substrate is RF-biased utilizing a substantially smaller power. Also, in a magnetron system, since the magnetic field increases the effective system pressure [2], the plasma density and electron temperature become weakly dependent on pressure for the low pressure regime studied.

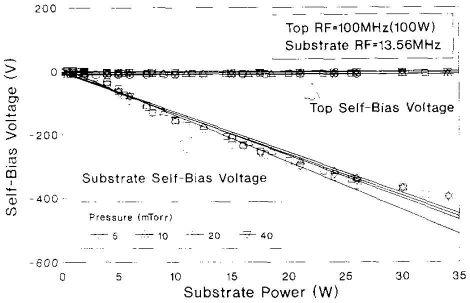

Fig. 4. Substrate self-bias dependence on Ar pressure and substrate RF (13.56 MHz) power. Plasma generating upper electrode RF is 100 MHz (100 W).

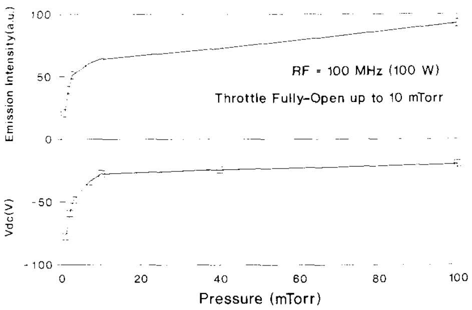

Fig. 5. Effects of pressure on emission intensity of Ar (419.9 nm) and self-bias voltage of upper electrode. Plasma generating RF is 100 MHz with a constant power of 100 W.

Fig. 6 shows the effects of varying the plasma generating RF power. The plasma potential, measured by a Langmuir probe 20 mm from the symmetrical axis and 15 mm from the substrate, and the self-bias of the top electrode showed insignificant dependence on the plasma generating power and also on the substrate RF power up to 30 W. As shown in this data, the ion bombardment energy on the substrate, i.e., the difference between the time-averaged plasma potential and self-bias, can be varied and reduced to almost zero for the non-biased substrate. This is observed in our system because the plasma potential becomes very close to ground when the shield is biased slightly negatively (-5 V). The effects of the biased shield have been discussed in detail [18].

If the substrate power is held constant, the substrate self-bias becomes slightly less for the higher plasma generating RF power. This is caused by the decrease in plasma impedance due to higher plasma density. The appreciable increase in ion flux, which increases proportionally with the ion density for a given field, was verified by monitoring the ion current with the substrate dc-biased using an external dc power source.

In all of the dual RF excitation data, an almost linear dependence of the substrate self-bias voltage on RF power is observed. The linear relationship of the self-bias voltage and RF power can be explained as follows:
Since,

$$P_{\mathrm{subs}} = I_{\mathrm{dc}} \cdot V_{\mathrm{dc}}. \tag{4}$$

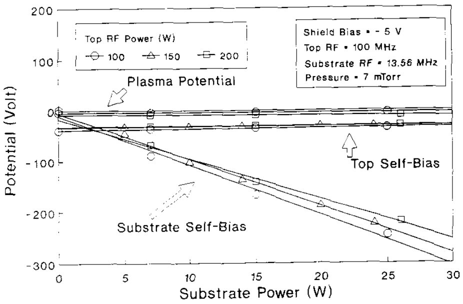

Fig. 6. Self-biases and plasma potential dependence on upper electrode RF (100 MHz) power. Substrate RF is 13.56 MHz. Plasma potential is measured 20 mm from axial center and 15 mm from substrate. Shield is biased -5 V to reduce plasma potential. Argon pressure is 7 mTorr.

and

$$I_{\mathrm{dc}} \propto n \cdot Te^{0.5} = \text{constant}, \tag{5}$$

combining the above two equations shows

$$V_{\mathrm{dc}} \propto P_{\mathrm{subs}}. \tag{6}$$

The latter follows because the small substrate power P_{subs} is assumed to not perturb the discharge; hence n and Te are unchanged. If the substrate power becomes comparable to the upper electrode power, then the above argument is incorrect.

B. Dual RF excitation in CF_4

The dual RF excitation data of Figs. 3–6 are obtained for argon discharges. In this section, the control of ion bombardment energy in a CF_4 plasma is described. Fig. 7 shows the time-average plasma potential and the self-bias voltages when a known percentage of CF_4 is mixed with Ar. The data indicates that the plasma potential increases gradually with the increase in CF_4 concentration. Interestingly, however, the difference between the plasma potential and the floating potential of the probe, which is a linear function of the electron temperature and inversely proportional to the log of the ion to electron mass ratio, remains constant.

Additional results on the dual RF excitation CF_4 plasma are shown in Figs. 8 and 9. Fig. 8 shows a linear dependence of the substrate self-bias voltage on the substrate RF power. The data shows that the substrate self-bias can be accurately controlled by a proper selection of the excitation frequency and the RF-biasing power for Ar/CF_4 mixture.

In contact hole etching of SiO_2 using fluorinated gases, we have often experienced a simultaneous shift in self-bias voltage when the polysilicon substrate is exposed to the plasma. Fig. 9 compares the variation in the self-biases for Si and SiO_2 substrates. A blanket Si wafer results in slightly less self-bias voltage than a substrate with 1 μm thermal oxide. For reference, the substrate RF-bias data of 5% CF_4 in Ar mixture is also shown. In conventional RIE, the oxide etch process is often run in a self-bias control mode rather than with a fixed power. Since the etched

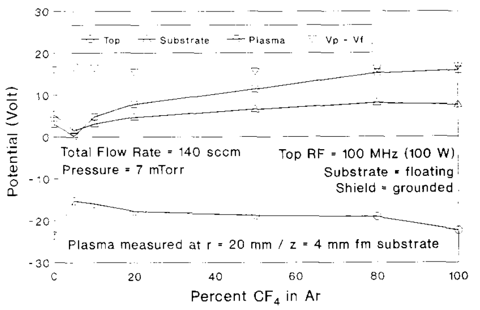

Fig. 7. Self-biases and plasma potential dependence on CF_4 concentration in Argon. Upper electrode RF is 100 MHz (100 W). Plasma potential measured from 20 mm from axial center and 4 mm from substrate. Total flow rate is 140 sccm. Pressure is 7 mTorr.

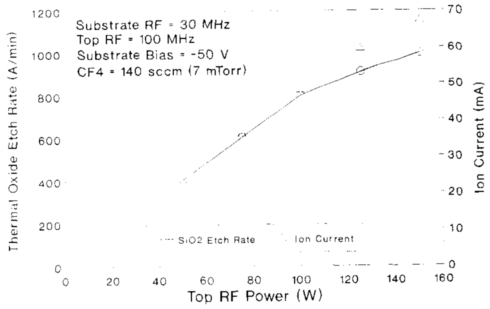

Fig. 10. Thermal Oxide etch rate and ion current dependence on upper electrode RF power. Substrate self-bias is maintained at −50 V by 30 MHz RF-biasing. Substrate ion current is measured using Si wafer dc-biasing. Process gas is CF_4. Pressure is 7 mTorr.

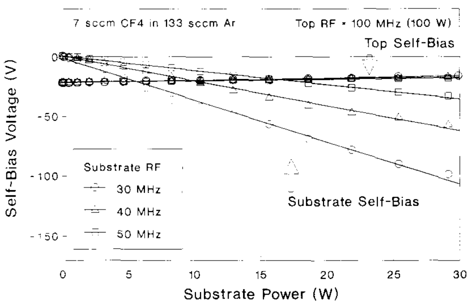

Fig. 8. Self-bias dependence on substrate frequency and power. Upper electrode RF is 100 MHz (100 W). Process gas is 5% CF_4 in Ar by volume. Pressure is 7 mTorr.

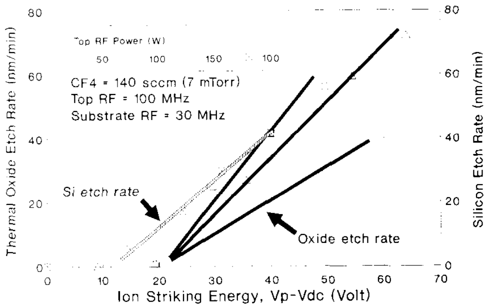

Fig. 11. Thermal Oxide etch rate vs ion striking energy ($Vp - V_{dc}$). Substrate is biased by 30 MHz. Plasma generating upper electrode RF (100 MHz) power is varied from 50 to 150 W. Plasma potential is measured 5 mm from substrate. Silicon etch rate for 100 W upper electrode RF power is shown in dashed line.

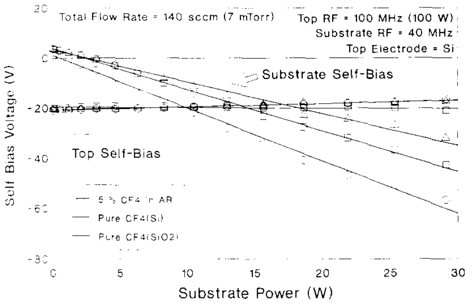

Fig. 9. Substrate self-bias dependence on substrate RF (40 MHz) power for Si and SiO_2 substrate. Plasma generating upper electrode RF is 100 MHz (100 W). Pressure is 7 mTorr.

profile depends strongly on the ion bombardment energy, the self-bias control is preferred over the constant power process. Therefore, the shift in self-bias voltage due to the change in substrate type, gas composition and area ratio especially during the over etch steps must be corrected.

The control of the plasma density is demonstrated in Fig. 10. The SiO_2 etch rate dependency on the top RF power shows that the etch rate increases with the increase in the plasma generating upper electrode RF power. For a constant substrate self-bias of −50 V, the etch rate increases consistently with the ion current up to 800 Å/min, then the etch rate begins to deviate from the ion current increase. The difference is perhaps caused by the presence of low energy ions due to collisions with etch byproducts or due to a sublinear scaling of density with power. Further study is required to identify the rate-limiting factors.

Fig. 11 shows the effects of varying the ion striking energy in SiO_2 etching for three different upper electrode RF powers. When we gradually varied the ion bombardment energy, we found the critical minimum ion bombardment energy of $E_{crit} \cong 19$ V is required to etch SiO_2 in CF_4 plasma. This is very close to the threshold of sputtering energy (~ 17 V) of Ar ions reported for quartz [25]. Also, the silicon etch rate for an upper electrode RF power of 100 W is shown as a dashed line.

It should be remembered that the ability to control the ion bombardment energy at the low energy regime (< 19 V) is extremely important. Since for any materials requiring less bombardment energy than the threshold, we would be able to etch with complete selectivity over SiO_2 and the low energy ions will still provide the directionality required. Thus, this opens many doors to achieve highly selective etching of various films with different etch threshold energies.

IV. CONCLUSIONS

It has been shown that by utilizing the dual RF excitation plasma equipment, the bombardment energy of ions can be accurately and independently controlled for both conductive and insulating substrates. In this study, we have categorized all the dual RF plasma processing into two modes. In "sputter" mode, a relatively low frequency (less than 20 MHz) electric field is applied to the plasma generating electrode, hence a substantially large negative self-bias voltage is obtained. On the other hand, the "RIE" mode requires significantly higher RF such as 200 MHz at the plasma generating electrode to minimize sputtering of electrode materials. The "RIE" mode of operation can be also applied to plasma CVD, dry cleaning and resist ashing with minimum levels of substrate damage and metal contamination by changing the process gases [5], [26].

The independent control of the ion density and the ion bombardment energy has been demonstrated for CF_4 etching of thermal oxide and confirmed that the thermal oxide etch rate increases linearly with the bombarding energy of the positive ions. By accurately controlling the ion bombardment energy, a critical energy of 19 V required for SiO_2 etching has been determined. The implication is that highly selecting etching of various thin films required for future semiconductor device manufacturing becomes highly possible through the dual RF excitation process.

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His research activities include 260 original papers and 190 patent applications. He received the Ichimura Award in 1979, the Teshima Award in 1987, and the Inoue Harushige Award in 1989. He serves as a General Chairman of the International Symposium on Power Semiconductor Devices and of the Institute of Basic Semiconductor Technology Development (Ultra Clean Society).

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