

The origins of self-bias on dielectric substrates in RF plasma processing

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Abstract

Negative biasing of dielectric substrates in plasmas is frequently applied to thin film deposition and etching in order to control impact energies onto the surface, which is usually done by contacting the dielectric substrates to an RF-driven electrode. The value of the bias on the surface of a dielectric substrate is difficult to monitor during plasma processing. In this work, we show that the self-bias on a dielectric substrate is determined by the plasma conditions as well as the thickness of the dielectric substrate. The difference between the actual self-bias on the surface of a dielectric substrate and the self-bias on the driven electrode can be very large. We propose a simple model to interpret the experimental results, in which the electron temperature and the plasma density as well as the dielectric thickness or dielectric constant play an important role in determining the actual bias on the dielectric substrate.

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1. Introduction

Dielectric materials have advantages in many important applications, such as electrical insulation, optical transparency, flexibility, low density and low cost. Dielectric substrates can be used in plasma deposition, etching and surface treatment processes. It is well known that the impact energy of the plasma ion species affects the deposition process and the material properties in a significant way. For example, it can dramatically influence the deposition rate, the density of the film, adhesion property, intrinsic stress, surface morphology and microstructure. While control of the energy of the plasma ion species can be achieved by a number of methods, the most convenient and effective one is to apply a negative bias. In the case of non-conducting substrates, this can be achieved by means of an electrode placed at the rear of the substrate and powered by a high frequency or pulsed power source. As a response to the oscillating RF potential, a self-bias is formed on the substrate surface. This self-bias is a result of the difference

in mobility between ions and electrons and the need to draw a zero net current in equilibrium.

It will introduce complexity and change substrate surface condition if one directly measures the self-bias on the surface of a substrate, in particular, when dielectric substrates are used. To avoid this complexity, the self-bias is often assumed to be equal to that on the rear electrode. Experimental results obtained using different dielectric substrates with RF bias are often compared without taking into account the effect of plasma parameters, thickness and the dielectric properties of the substrates on the formation of the self-bias. While this approach may be valid for very thin dielectric substrates with high permittivity and where fine process control is not required, for many applications, it is important to understand in detail the formation mechanism of self-bias on RF biased dielectric substrates. Fine control of bias is important for applications such as large-scale displays and optical thin film devices, which need a degree of control of the material properties and may require thick dielectric substrates to ensure device durability.

Charles et al. [1] observed using a Langmuir probe an increase in surface potential on a dielectric layer of silicon oxide coated on the walls of a RF plasma chamber. Howling et al. [2] measured surface charge accumulated on a dielectric

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substrate after switching off the RF plasma. Kim et al. [3] recently measured the self-bias voltage in situ on a silicon wafer placed on the surface of a dielectric substrate backed by a driven RF electrode. Despite these studies, the degree of the influence of the plasma conditions on the self-bias is not known. In this paper, we report experimental work and theoretical modeling, quantifying the dependence of the self-bias on the plasma conditions and the properties of the dielectric substrate.

2. Experimental

The plasma was generated using an ENI OEM-6 B power supply with 13.56 MHz frequency. A planar electrode was used and covered at the front surface by a substrate. The planar cathode is 110 mm long and 55 mm wide. When a dielectric substrate was used, the dimensions of the dielectric substrates were 130 mm long and 75 mm wide. In some cases, an additional hollow cathode was placed near the front surface of the substrate (30 mm away) and connected to another RF supply. When two RF electrodes were used, RF phases were synchronized using an ENI VL-400 phase shift controller. The hollow cathode is an 80 mm long tube with 26 mm inner diameter. One end of the hollow cathode was blocked using an insulating plate. The chamber was electrically grounded. Base pressure in the vacuum system is better than $2\text{E}-6$ Torr. A Pfeiffer QMS 200 residual gas analyser was connected to the vacuum chamber via a leak valve to detect impurity levels. The argon gas used in this study has a purity of 99.999%. The argon flow used was approximately 4 orders of magnitude higher than the typical outgassing rate of chamber walls in this vacuum system. Substrates were Corning 7059 glass and p-type (100) silicon. Similar to the method reported by Kim et al. [3], a probe on substrate for detecting the substrate self-bias was connected to an oscilloscope and the probing site at the substrate was coated with conducting film. The area of the coating is approximately $2 \times 2 \text{ cm}^2$, much smaller than the substrate area ($\sim 90 \text{ cm}^2$). The connection between the probing site and the oscilloscope was appropriately shielded and a high resistance RF block was embedded between the probe site and the shielded cable. A Langmuir probe was used to measure plasma density and electron temperature. The Langmuir probe consists of a 0.20-mm diameter tungsten wire threaded through a ceramic (ALSINT) tube, which was inserted into a larger diameter stainless steel tube.

3. Theory

The equivalent circuit for RF bias used by Kim et al. [3] consists of three capacitors in series, C_s , C_d and C_b to describe the capacitance associated with the plasma sheath,

the dielectric capacitor including the insulating substrate and conducting holder, and RF matching network blocking capacitor, respectively. The disadvantage of this equivalent circuit is that the value of the blocking capacitor must be varied with the plasma conditions to give optimum matching. In addition, the capacitance of the sheath varies with the plasma density and the surface charge on the substrate.

As an alternative DC equivalent circuit for the system, we remove the matching network capacitor by including the measured voltages at the surface of the dielectric substrate and on the surface of the conducting electrode. This equivalent circuit is shown in Fig. 1, where V_p , V_d and V_b are the plasma potential, the dc self-bias on the dielectric substrate, and the dc self-bias on the surface of the conducting electrode, respectively.

At the interface of the dielectric substrate and the sheath, the displacement electric field continuity equation is:

$$\varepsilon E_d = \varepsilon_0 E_s + \sigma \quad (1)$$

Where ε and ε_0 are permittivity of the dielectric substrate and free space, respectively, σ is the charge density at the surface of the dielectric substrate, E_d and E_s are the electric field in the dielectric substrate and the plasma sheath at the interface respectively. If d is the thickness of the dielectric substrate, then $dE_d = V_b - V_d$. We then have:

$$V_b - V_d = \frac{\varepsilon_0 E_s + \sigma}{\varepsilon} d \quad (2)$$

Applying the Child–Langmuir law to current flow in the plasma sheath, following the derivation in Refs. [4,5] and substituting the Bohm velocity with $(eT/M)^{0.5}$, where e is the electron charge density, T is the electron temperature in eV and M is the mass of ion, the equilibrium RF sheath thickness can be expressed as:

$$L = \left(\frac{\sqrt{2} K_i \varepsilon_0}{e} \right)^{0.5} \frac{V_d^{0.75}}{n^{0.5} (T)^{0.25}} \quad (3)$$

K_i is a constant for which we use the value of 0.82 [4] and n is the ion density in plasma. The Bohm velocity assumes that the sheath potential markedly larger than kT/e , which is generally hold for RF plasmas with biasing electrode for substrate. Note the sheath width is defined as the distance

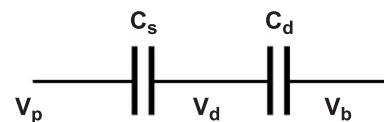


Fig. 1. The equivalent DC circuit for a dielectric substrate placed on electrode in a plasma. V_p , V_d and V_b are the plasma potential, the dc self-bias on the dielectric substrate, and the dc self-bias on the surface of the conducting electrode respectively, and C_s and C_d are the effective capacitances of the sheath and the dielectric substrate capacitor, respectively.

from the surface to where plasma potential is equal to zero. The Child–Langmuir law also predicts [5] that the electric field at the sheath edge of the substrate has a relationship $V_d = 3/4LE_s$, Eq. (2) can be expressed as:

$$V_b - V_d = \frac{d}{\varepsilon} \left(\sigma + \frac{4}{3} \varepsilon_0 \frac{n^{0.5} (TV_d)^{0.25}}{\left(\frac{\sqrt{2} K_i \varepsilon_0}{e} \right)^{0.5}} \right) \quad (4)$$

Where n is ion density and T is electron temperature. The electron temperature was experimentally measured and found to be approximately constant at about 3 eV.

4. Results and discussion

The self-bias appearing on both the planar electrode and the top surface of the substrate were measured as a function of operating pressure and dielectric substrate thickness. The ratio of the self-bias on the substrate to that on the electrode is plotted in Fig. 2. The 0-mm thickness data point on this figure represents the result for a bare doped silicon substrate. The bias ratio is of practical interest, because the self-bias on a dielectric substrate is difficult to measure so the electrode self-bias is monitored instead. We found in this work that, over a wide range of RF power, the ratio is constant except at very weak (<25 W) RF power when the plasma is not useful for deposition or etching. In Fig. 2, over the range of pressure studied, the bias ratio for the silicon substrate is close to unity as expected for a conducting substrate. In all cases, for a glass substrate, the bias ratio is strongly dependent on the operating pressure and substrate thickness. With increase of substrate thickness and operating pressure, the bias ratio decreases. The data show that the self-bias on a dielectric substrate cannot be

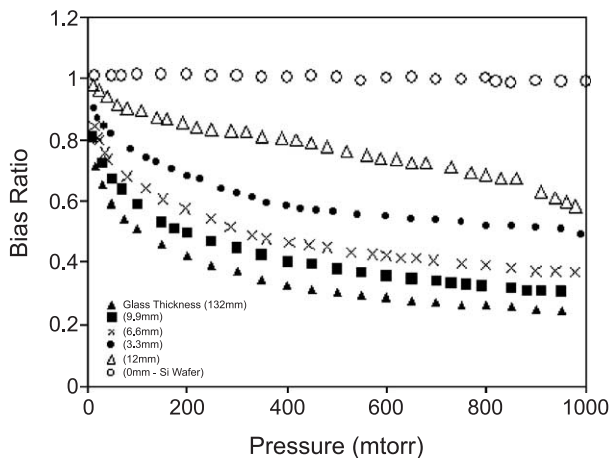


Fig. 2. The ratio of the self-bias on the substrate to that on the electrode plotted as a function of the thickness of the dielectric substrate and operating pressure. The 0-mm thickness data point on this figure represents the result for a bare doped silicon substrate.

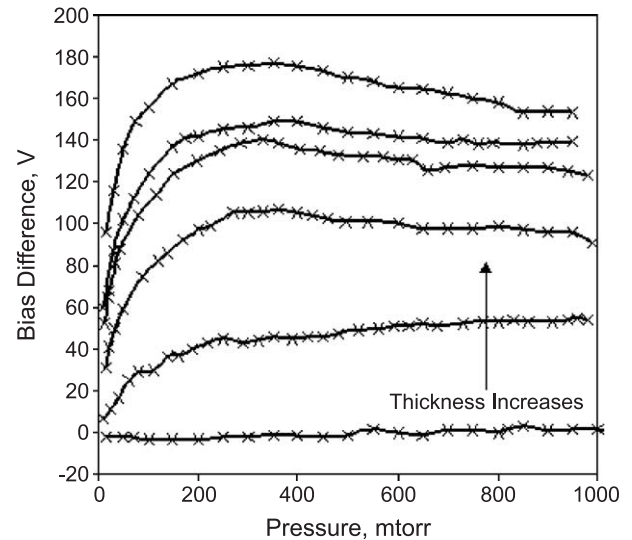


Fig. 3. The difference in self-bias between the electrode and the front substrate surface as a function of dielectric substrate thickness and operating pressure for the substrate samples shown in Fig. 2.

regarded simply as equal to or even proportional to that on the electrode, even for thin dielectric substrates (in the thickness range 1–3 mm). For example, for a pressure equal to 500 mTorr, a 1.2-mm substrate suffers a 20% self-bias reduction and a 3.3-mm substrate has a self-bias reduction of about 40%. At low pressure (say 10 mTorr), the self-bias reduction is much less as shown in the figure.

The same data is shown in Fig. 3 plotted as the difference in bias between the electrode and the front substrate surface. For all glass substrates, the bias difference increases rapidly at low pressures. In the high-pressure range, however, the bias difference decreases slowly for all but the 1.2-mm-thick glass substrate.

The data in Figs. 2 and 3 indicate that the effect of substrate thickness on self-bias cannot be regarded as due only to the polarisation of the substrate dielectric, but also depends on the accumulation of true surface charge determined by the plasma conditions. We can estimate the true surface charge density from Eq. (4) by expressing it as:

$$\sigma = \varepsilon \left(\frac{V_b - V_d}{d} - \frac{4}{3} \frac{\varepsilon_0}{\varepsilon} \frac{n^{0.5} (TV_d)^{0.25}}{\left(\frac{\sqrt{2} K_i \varepsilon_0}{e} \right)^{0.5}} \right) \quad (5)$$

Note that the first term represents the contribution from the polarisation charge, while the second term represents the contribution from the true surface charge. According to this simple model, the plasma parameters of electron temperature and plasma density, together with the electric field in the sheath, affect the charge density and thus the self-bias on the dielectric substrate surface. Eq. (5) predicts that the charge density can be positive or negative. The charge density is negative if the self-bias on the surface is close to

the bias on the electrode so that the first term in Eq. (5) is very small. Negative surface charge will also occur if the plasma density is high enough.

In order to determine the effect of the plasma conditions on the value of the surface charge on the dielectric substrate, we performed Langmuir probe measurements at an operating pressure of 116 mTorr and an RF power of 120 W as a function of the thickness of the dielectric substrate. As shown in Fig. 4, the plasma density varies only slightly over a wide range of substrate thickness; in particular, we note that in the second term in Eq. (5) the plasma density scales with square root. The electron temperature remains almost constant about 2.8 eV.

Pressure affects the plasma (or ion) density more significantly than the thickness of the substrate. Fig. 5 shows the ion density as a function of operating pressure for a silicon substrate at 120 W RF power. In the low-pressure range up to about 200 mTorr, the ion density increases with the operating pressure, and then decreases. The initial increase at low pressure we interpret as an increase in ionising collisions due to an increase in the density of species to be ionised. We interpret the decrease at higher pressure as being due to a further increase in collisions with background neutrals reducing the number of electrons that are accelerated to ionising energies.

According to Eq. (5), the surface charge density is proportional to the square root of plasma density. Thus, over the range of the operating pressure investigated the variation of the true charge density (the second term) due to the variation of plasma density is predicted to be only two to three times.

Applying the data in Figs. 4 and 5 and assuming that the ion density as a function of pressure is the same for all substrate thicknesses, we calculated the charge density and plot it in Fig. 6, assuming that the dielectric constant of the glass substrate is 7. The value of temperature used was 2.8 eV and the measured values of V_d and V_b from Figs. 2 and 3.

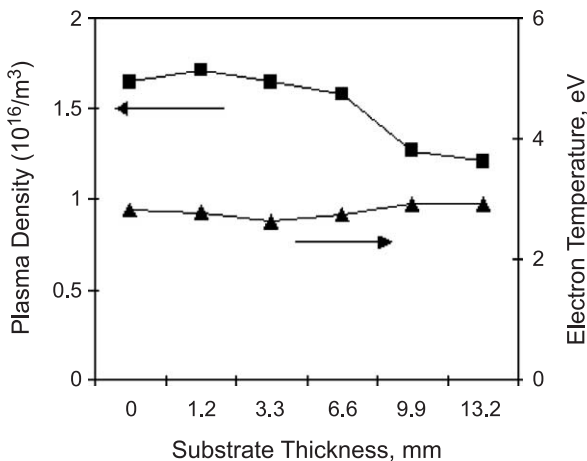


Fig. 4. The plasma density and the electron temperature plotted as a function of the thickness of the dielectric substrate.

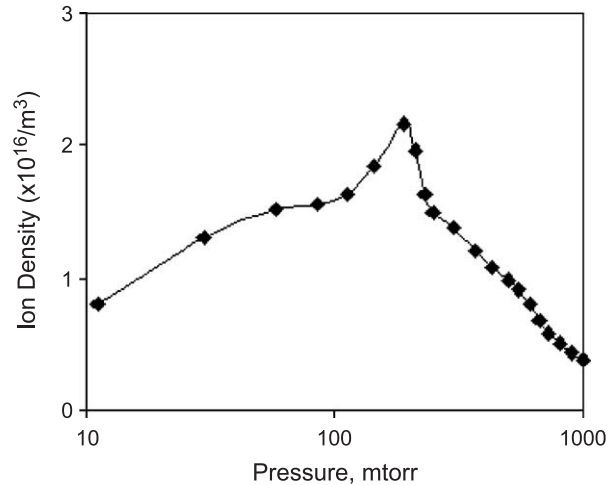


Fig. 5. The ion density 30 mm from the dielectric surface as a function of the operating pressure, measured using a probe.

The charge density in Fig. 6 is consistent with experimental results obtained by Howling et al. [2]. Their glass surface charge density was measured after immediately switching off the RF plasma. Once the plasma is switched off, there will be some leakage of charge from the surface. At pressures of less than about 30 mTorr, the charge density is close to zero, with some negative points. Sansonnens et al. [6] found that negative charge density could appear on glass substrates at low pressures or high RF power. This is predicted using Eq. (5). At high RF power, the plasma density increases so that the second (or the negative) term becomes larger. At low pressure, as shown in Fig. 2 or 3, the difference between the self-bias on substrate (V_d) and self-bias on the backing electrode (V_b) becomes smaller, thus the first term in Eq. (5) becomes smaller.

The results show that plasma conditions are important in order to estimate self-bias on dielectric substrate surfaces. This was further investigated by introducing a second plasma

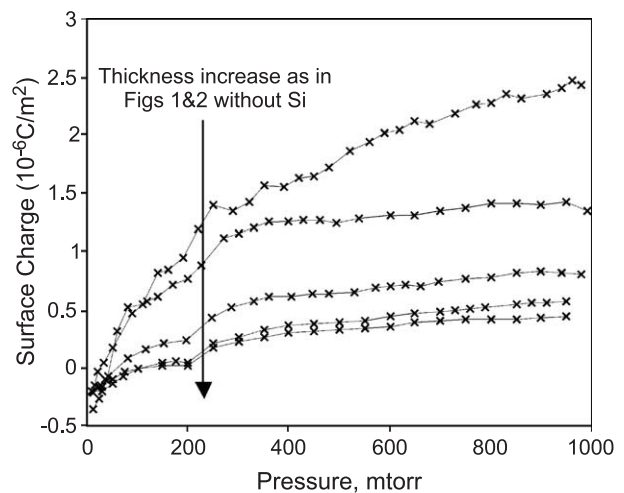


Fig. 6. The charge density on the dielectric surface calculated as explained in the text using Eq. (5) as a function of the operating pressure for different thickness of dielectric substrates.

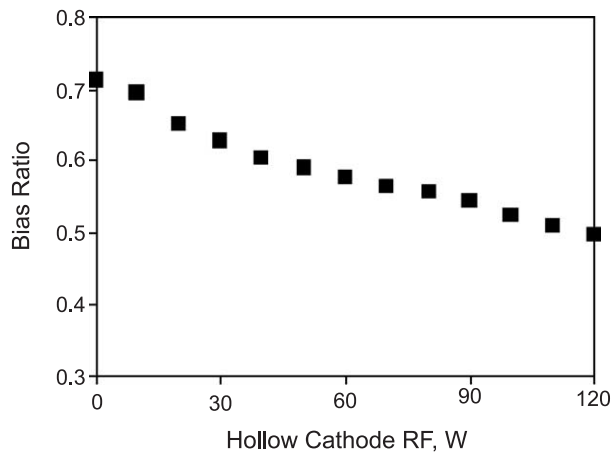


Fig. 7. The self-bias ratio as a function of RF power delivered to the second electrode.

source in front of the substrate. In this experiment, we placed a hollow cathode 30 mm away from the substrate. The two RF sources were synchronised with a phase difference of 180° in order to avoid beating effects.

At a pressure of 116 mtorr and planar cathode RF power of 120 W, we measured the effect of RF power of the hollow cathode on the substrate self-bias for a 3.3-mm glass substrate. Fig. 7 shows that the bias ratio decreases with an increase of hollow cathode RF power. This can be understood according to Eq. (5). Increasing hollow cathode RF power results in an ion density increase, thus reducing V_d and the self-bias ratio.

5. Conclusion

We have shown that the self-bias on a dielectric substrate is determined by the plasma conditions as well as the thickness of the dielectric substrate. This work opens a new approach for precise plasma control in deposition and etching when dielectric substrates are used. Self-bias has a very strong influence on deposition and etching results. Many previously observed dependences on individual plasma

parameters should be better understood in terms of changes in the self-bias alone.

Self-bias on dielectric substrates when they are connected to an RF electrode is not equal to the self-bias of the driven electrode, and is not simply scalable using the dielectric capacitor of the substrate. The difference between the actual self-bias on a dielectric substrate and the self-bias on the driven electrode can be very large compared with the self-bias on the electrode, depending on the plasma conditions as well as the thickness of the dielectric substrates. A simple model was proposed in this paper to interpret the experimental results.

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