Plasma Effects on Electrostatic Chuck Characteristics on Capacitive RF Discharge

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Johnsen-Rahbek electrostatic chuck (ESC) is installed on the cathode side of a capacitive RF discharge, and the ESC voltage-current (V-I) characteristic is measured under various conditions. First, the reference V-I curve is obtained for a grounded aluminum (Al) wafer without discharge. The observed nonlinear characteristic is attributed to the field emission of electrons at irregular contacting surfaces. When the discharge is turned on with an electrically floating wafer, the V-I curve shifts from the reference curve toward the negative direction along the chuck voltage axis. The amount of shifted chuck voltage coincides with the self-bias DC voltage induced on the wafer. This plasma effect on the V-I characteristics can be explained well in terms of the effective chuck voltage, taking into account the self-bias. On the other hand, the replacement of the Al wafer with a silicon (Si) wafer leads to a considerable reduction in the chuck current. When a thin Al foil is inserted between the Si wafer and the aluminum nitride (AlN) spacer layer, the chuck current recovers upto the reference value, suggesting that the Johnsen-Rahbek effect is extremely sensitive to the electrical and mechanical properties of the contacting interface.

Keywords: electrostatic chuck, Johnsen-Rahbek, capacitive discharge, self-bias DC voltage

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Electrostatic chuck (ESC) is widely used for holding silicon wafers and controlling their temperature during the plasma-assisted processing of semiconductors. There are two holding configurations of ESC: the Coulomb type [1–3], using an insulating spacer layer (volume resistivity $\rho > 10^{14}\ \Omega$-cm), and the Johnsen-Rahbek (J-R) type [4, 5], using a semiconductive spacer layer ($\rho = 10^{10}$-$10^{12}\ \Omega$-cm) between plates (i.e., chuck electrode and wafer). The electrostatic holding force in the Coulomb type stems is generated due to the opposite polarity surface charges that appear on the wafer and chuck electrode at high applied voltages. A new experiment using thin plastic films and insulating sealant has been reported on the bipolar configuration of Coulomb-type ESC [6].

In the J-R type, a very strong holding force is achieved even at low chuck voltages due to the high electric fields between the narrow gaps distributed over the spacer layer with surface irregularities. In comparison to the Coulomb type, the J-R type is very sensitive to the following physical conditions of the contacting surface: electrical conductivities, residual charges, surface roughness on submicroscopic scales, and large-scale flatness of two plates. Many questions arise on how such conditions influence clamping and declamping behaviors in actual ESC systems. Examples of ESC-related limitations include poor process repeatability caused by residual charges, film damage induced by the chuck current, and wafer cracking when raised by lift pins.

To solve these problems, a deeper understanding of the ESC-holding mechanism is required, particularly in practical plasma conditions. In this paper, we present a basic study on J-R ESC installed in a parallel-plate discharge, i.e., capacitive coupled plasma (CCP). The voltage-current (V-I) characteristics of ESC is measured for a variety of discharge powers, comparing the silicon wafer with the aluminum wafer. Notable effects of RF-induced self-bias voltage on V-I characteristics were observed, along with the influence of contacting material surfaces.

The experimental apparatus for a CCP discharge with a unipolar J-R ESC in a grounded stainless-steel chamber with a diameter of 300 mm, as shown in Fig. 1. An RF plasma at 13.56 MHz was produced in an argon atmosphere at a pressure of ~100 mTorr and a flow rate of 100 sccm in a 30 mm gap between a grounded anode and a cathode, which had a diameter of 200 mm and consisted of a RF electrode, ESC, and wafer. A wafer of aluminum (Al) or a silicon (Si) slab with 100-mm-radius was clamped next to the J-R ESC with radius $r = 100$ mm, where a molybdenum chuck electrode was embedded in a 10-mm-thick AlN layer with separation $l = 0.61$ mm (spacer layer thickness) from the contacting wafer surface. The volume resistivity of AlN used in the present experiment is

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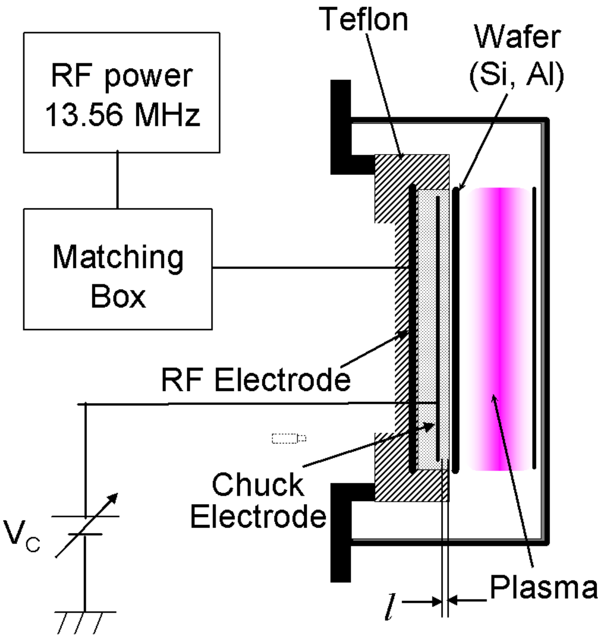

Fig. 1 Schematic of CCP apparatus used with the J-R ESC system.

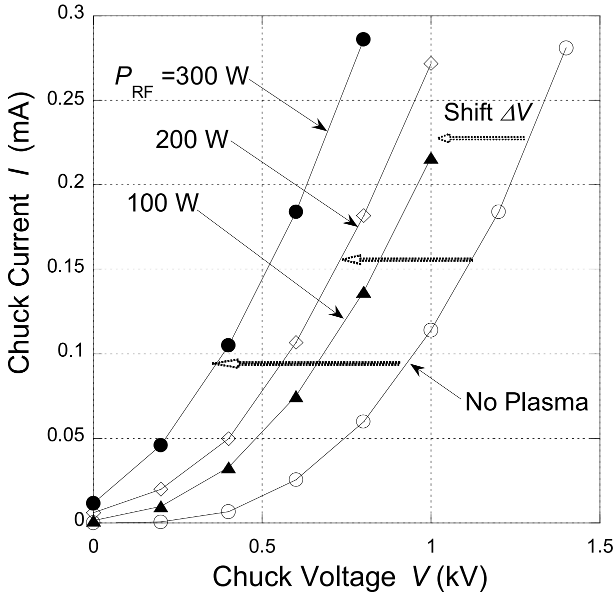

Fig. 2 Voltage-current characteristics for the grounded Al wafer without plasma.

Table 1 Chuck current I, voltage difference δV, and electric field E measured for various chuck voltages V.

V (kV)	I (μA)	δV (kV)	E (MV/m)
0.2	0.7	0.193	193
0.4	6.8	0.331	331
0.6	25.7	0.338	338
0.8	60.0	0.188	188
1.0	114.0	−0.163	-
1.2	188.0	−0.677	-
1.4	286.0	−1.460	-

$\rho = 5 \times 10^{10}\,\Omega$-cm. The net contacting surface is reduced to 14% of the projected area of the chuck electrode because numerous embosses of diameter 2 mm and height $h = 50\,\mu$m were prepared for helium gas cooling. Therefore, the total resistance R of the AlN layer between the chuck electrode and the wafer is provided by a series connections of the base part and the embossed part as

$$R = \rho\left(\frac{l-h}{S}\right) + \rho\,\frac{h}{0.14S} \qquad (1)$$

where the chuck area $S = \pi r^2$, and by substituting the parameters into Eq. (1), we get $R = 10.2\,\mathrm{M\Omega}$.

The chuck voltage V in a range from −1.5 kV to +1.5 kV is applied to the chuck electrode through which the chuck current I flows to the grounded anode and chamber wall, forming a current loop via the AlN layer, clamped wafer (Si or Al), sheath, and plasma bulk.

To obtain reference data for the V-I characteristics, chuck current I was measured as a function of the electrostatic chuck voltage V without discharge, where the 0.2-mm-thick Al wafer was grounded. Here, the measurements were performed in vacuum to avoid any influence of humidity in air under high applied voltage. The measured V-I curve is plotted in Fig. 2, where a symmetry with respect to the polarity of the chuck voltage is confirmed. The straight dashed line in Fig. 2 indicates the application of Ohm's law for the AlN layer of $R = 10.2\,\mathrm{M\Omega}$, given by Eq. (1). It is observed that the chuck current measured below ~0.5 kV was much lower than the values predicted using Ohm's law. This clearly suggests the existence of a very large contact resistance of a thin contacting layer, to which the voltage difference $\delta V = V - RI$ is applied. On the other hand, the chuck current measured at high voltages ($V > 1$ kV) drastically increases, exceeding the values predicted using Ohm's law. The mechanism for this is attributed to the field emission of electrons, as discussed below.

Table 1 shows the numerical data of chuck current I and voltage difference δV for the positive chuck voltage. At low chuck voltages ($V < 0.5$ kV), the voltage applied to the contacting layer (δV) is approximately equal to the chuck voltage (V). In other words, most of the chuck voltage is applied to the thin irregular contacting layer, which has a gap distance $d = 0.8$-$1.6\,\mu$m estimated from surface roughness measured using AFM (Atomic Force Microscope). Assuming $d = 1\,\mu$m, the electric field $E = \delta V/d$ was calculated (see Table 1), which increased to 300 MV/m or higher at $V > 0.4$ kV. An intense electric field such as 500 MV/m is known to induce the field emission of electrons [7, 8]. The chuck current nonlinearly increased above 0.5 kV, as seen in Fig. 2, which is attributed to field emission, provides evidence for the Johnsen-Rahbek effect [9]. When the chuck voltage is increased, the emission current increases because of an increase in the field intensity and the emission area. At $V > 1\,\mathrm{kV}$, the polarity of the voltage difference δV was apparently inverted (see Table 1), where the current in the contacting layer flowed non-uniformly such that the simple formula of $\delta V = V - RI$ does not hold true anymore.

To investigate the effect of the plasma on the V-I characteristics, the Al wafer was floated and the RF power was applied to the RF electrode at various power settings in argon at 100 mTorr. Figure 3 shows the V-I curves measured in the discharge powers 100, 200, and 300 W. Here, only the positive part of the chuck voltage has been plotted for simplicity, and the reference curve is labeled "No Plasma" for comparison purposes. This reference curve is not identical to the curve in Fig. 2, since chuck current is very sensitive to the contacting surface conditions, as will be discussed later, and varies from wafer to wafer. We can see in Fig. 3 that the V-I curve shifts to "left" in parallel along the chuck voltage axis from the reference curve obtained without a plasma. This left shift was also observed in the negative part of the chuck voltage. The amount of left-shift voltage (ΔV) as a function of the discharge power is plotted as the closed circles in Fig. 4, where the error bars for ΔV indicate the data-scattering for various chuck currents.

Such voltage shift ΔV is presumably caused by a change in the floating potential of the wafer in the RF plasma. As is well-known in asymmetric CCP discharge, self-bias DC voltage (V_{DC}) appears on the cathode (the wafer in the present experiment) to ensure a time-averaged net current remains null in a RF cycle. To confirm this hypothesis, the wafer DC voltage (V_{DC}) was directly measured by a high-voltage high-impedance ($\sim 100\,\mathrm{M\Omega}$) probe. Figure 4 compares the measured V_{DC} (open circles) with the voltage shift ΔV (closed circles), where a relatively good coincidence between the absolute values of ΔV and V_{DC} were obtained.

This suggests the following mechanism for the plasma effect on the V-I characteristics. The insertion in Fig. 4 illustrates the potential distribution in the AlN spacer layer of thickness l between the chuck electrode and the wafer contacting surface. When the discharge is off, the wafer is grounded, as indicated by the dashed line. With the discharge turned on, the wafer potential drops to V_{DC} (< 0) for the same chuck voltage V_{C}. Consequently, the voltage difference $V_{\mathrm{C}} - V_{\mathrm{DC}}$ in the spacer layer increases by $|V_{\mathrm{DC}}|$, such that the voltage shift $|\Delta V|$ in the V-I curve coincides with $|V_{\mathrm{DC}}|$.

Since the wafer holding force and chuck current are determined by the electric field $|V_C - V_{\mathrm{DC}}|/l$ in the spacer layer, the folding force increases with the discharge power for the positive chuck voltage ($V_{\mathrm{C}} > 0$) because V_{DC} is always negative. In contrast, the negative chuck voltage gives less holding force at a higher power: the holding force and chuck current will vanish at critical power, yielding $V_{\mathrm{DC}} = V_{\mathrm{C}}$. Therefore, while the wafer holding force generally varies with the discharge power, the force can be fixed by keeping the chuck current constant by controlling the chuck voltage.

Since, in the actual plasma-processing of a semiconductor Si wafers are conventionally used, we replaced a 200-mm-diameter, 0.2-mm-thick Al wafer with a Si wafer (non-doped intrinsic silicon) of the same diameter and

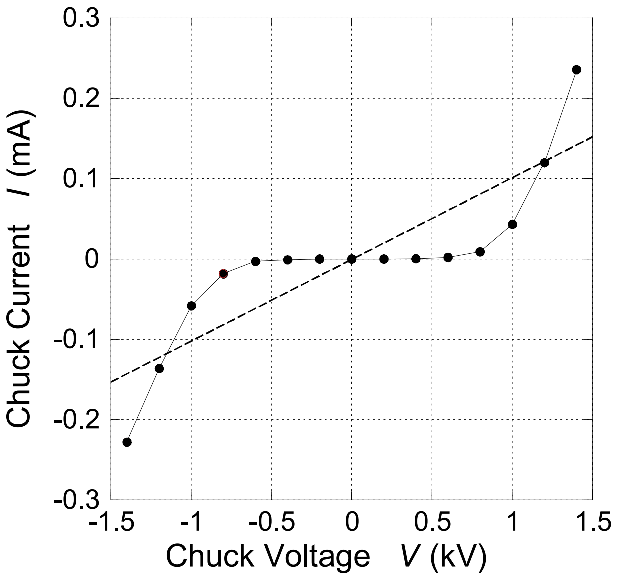

Fig. 3 Voltage-current characteristics for various discharge powers P_{RF}, together with the reference data (no plasma).

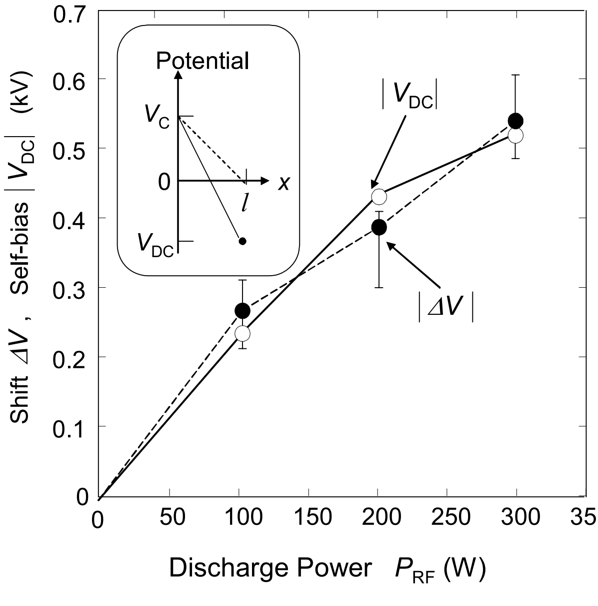

Fig. 4 Voltage shift ΔV and self-bias V_{DC} as a function of RF discharge power P_{RF}. The insertion illustrates the potential profile in an AlN spacer layer of thickness l.

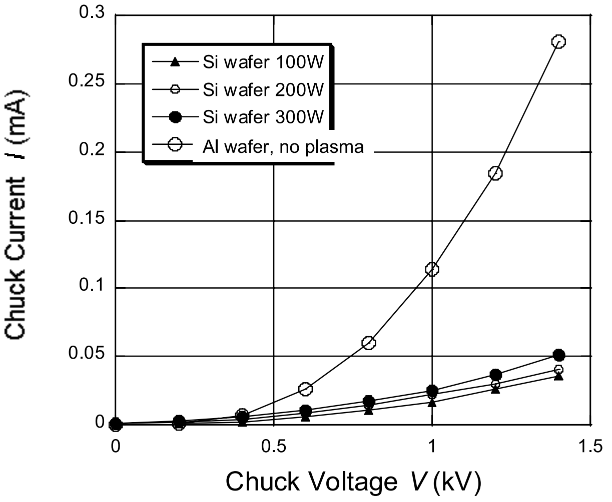

Fig. 5 Voltage-current characteristics for various discharge powers using a Si wafer, in comparison to Al wafer data without plasma.

0.7 mm in thickness. The V-I curves measured at the discharge power of 100 W, 200 W, and 300 W are shown in Fig. 5, along with the reference curve obtained by the grounded Al wafer. Compared with the Al wafer data shown in Fig. 3, the chuck current drastically decreased, although the V-I curve shift brought about by the plasma effect was again observed with the same V_{DC} as in Fig. 4. This chuck current reduction implies the weaker electric field and the weaker chuck force.

The origins of this chuck current reduction should be carefully considered. The J-R effect is very sensitive to contact resistance, which basically depends on the contact area and surface resistivity as well as the native oxide layer of the Si and Al slabs. The contact area depends on the large-scale flatness of both the AlN surface and the Si or Al wafer surface, in addition to the small-scale surface roughness of both contacting interfaces. Furthermore, an observed major chuck current is attributed to field emission, and hence the gap length distribution at the interface can significantly modify the total current. Therefore, it may be difficult to identify the main factors influencing the observed current reduction. One possible reason might be the difference in the thickness and rigidness between the wafers—the Si slab of 0.7 mm thickness is more rigid than the Al slab of 0.2 mm thickness—and hence the Al slab will come into contact with the AlN surface more smoothly than the Si slab would when pressed by electrostatic force.

An additional experiment was performed by completely inserting a very thin Al foil (12.5 μm thickness) between the Si wafer and the AlN layer surface. In other words, the rear surface of the Si wafer was modified by attaching a soft Al foil. Applying the chuck voltage in this system showed a recovery of the chuck current to the same levels shown in Fig. 3. At the same time, the Si wafer was observed to detach from the ESC and inclined by 1 mm at the wafer top toward the plasma side. In other words, the ESC holds only the Al foil, and the Si wafer was attracted by the positive space charge in the sheath, such that it inclined toward the plasma side. This simple experiment suggests that ensuring tight contact with a Si wafer is possible f the Si rear surface in contact with the dielectric layer could be modified by suitable means.

In conclusion, the fundamental characteristics of Johnsen-Rahbek type ESC installed in CCP apparatus were investigated. Measurements of V-I curves without a plasma revealed the essential features of J-R type ESC: large contact resistance, high voltage applied to a thin contacting layer, and a nonlinear increase in the chuck current, due to field emission. When the RF discharge is switched on, the V-I curve was found to shift toward the negative voltage side. The magnitude of the voltage shift $|\Delta V|$ coincided with that of the self-bias DC voltage ($|V_{DC}|$). This plasma effect was interpreted using the net chucking voltage of $|V_C - V_{DC}|$, together with implications found in practical plasma processing. Although this effect was found in the CCP, it can also be seen in plasma devices such as ICP, SWP, ECR, and helicon sources, when the RF bias is applied to a substrate stage using J-R ESC. Finally, a comparison of the Al wafer and the Si wafer demonstrated that J-R ESC is extremely sensitive to the conditions of contacting surfaces.

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