ANALYSIS OF COULOMB AND JOHNSEN-RAHBEK ELECTROSTATIC CHUCK PERFORMANCE FOR EUV LITHOGRAPHY

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INTRODUCTION
The imaging system in extreme ultraviolet lithography (EUVL) incorporates a reflective mask that is subjected to non-telecentric illumination during exposure. As a result, any nonflatness (i.e., variation of the height) of the pattern surface results in image placement errors on the device wafer. For this reason, it is imperative that the frontside and backside of the reticle, as well as the electrostatic chuck (ESC), be exceptionally flat to meet the critical dimension control and overlay budget requirements. The EUVL Mask Standard, SEMI P37, specifies that the substrate surface nonflatness not exceed 100 nm peak-to-valley ($p-v$) [1]. SEMI P40, the EUVL Mask Chucking Standard, requires the chucking surface nonflatness to be less than 50 nm $p-v$ [2]. Consequently, EUVL depends upon the capability of an ESC to reduce the final mask nonflatness; the successful implementation of EUVL requires this flattening capability be characterized, predicted, and well-understood.

An ESC clamps a substrate to a dielectric chuck surface by electrostatic force. Two types of electrostatic chucks are the Coulomb and Johnsen-Rahbek (J-R) [3,4]. These are distinguished by the characteristics of their dielectrics and the resulting mechanism of clamping force generation. The Coulomb chuck functions like a conventional dielectric capacitor. The J-R dielectric has a large but finite resistance, so a current flows through it and the substrate when the surfaces are in contact and voltage is applied. Charge accumulates at the interface between substrate and dielectric. Since the thickness of the interface region is related to surface roughness, the charge separation is typically quite small, and strong electrostatic forces can be generated.

COULOMB STYLE CHUCK
For a monopolar Coulomb chuck, the electrostatic pressure, $P$, is given by:

$$ P = \frac{\varepsilon_o V^2 K^2}{2(t_D + K\delta)}, $$

where $V_o$ is the applied voltage, $K$ is the relative permittivity of the dielectric, $\varepsilon_o$ is the permittivity of free space ($8.85 \times 10^{-12}$ F/m), $t_D$ is the dielectric thickness, and $\delta$ is the total gap between the backside of the mask and the dielectric surface. For a given magnitude of applied voltage, the pressure generated by a monopolar chuck is four times larger than that from a bipolar chuck. Only monopolar chucks are examined in this paper.

A characteristic of the Coulomb chuck is that clamping pressure exists everywhere between the reticle and chuck. Typical values for $t_D$ in a Coulomb chuck are 100-200 µm and the $K\delta$ term in the denominator of the pressure equation is often an order of magnitude smaller than $t_D$. Thus, the clamping force is virtually unaffected in the presence of non-flat substrates or entrapped particles (considering relatively small gaps), as illustrated in Fig. 1.

JOHNSEN-RAHBEK STYLE CHUCK
Details of the clamping characteristics of a J-R chuck are illustrated in Fig. 2(a). When voltage is applied, charge accumulates along the rough chuck-substrate interface, or contact layer. This layer has a thickness $t_{CL}$ which is related to surface roughness, as illustrated in the figure. The properties of the chuck also depend on the resistances of the bulk dielectric ($R_v$) and the
contact layer ($R_{CL}$). In addition to the attractive force generated in the contact layer, a conventional Coulomb chuck force is also generated between the substrate and the chuck electrode.

![Diagram](image)

**FIGURE 1.** (a) Characteristics of a Coulomb chuck and (b) corresponding pressure distribution with an entrapped particle.

While the details of the accumulated charge in the contact layer are quite complicated, a phenomenological model of the J-R chuck force mechanism can be created by treating the contact layer as a small air gap capacitor, of thickness $t_{CL}$. The amount of charge deposited at the contact layer (or equivalently the voltage drop) can be related to the relative values of $R_V$ and $R_{CL}$, which function as a resistive divider. This results in the following expression for the clamping pressure, $P$:

$$P = P_{Coul} + P_{JR}$$ (2)

where,

$$P_{Coul} = \frac{\varepsilon_o V_o^2}{2} \left( \frac{K}{t_d + K(\delta + t_{CL})} \right)^2$$ (3)

and

$$P_{JR} = \frac{\alpha \varepsilon_o V_o^2}{2} \left( \frac{R_{CL}}{R_{CL} / R_V} \right)^2 \left( \frac{t_{CL}}{1 + \left( \frac{R_{CL}}{R_V} \right)} \right)$$ (4)

The parameter $\alpha$ is an empirical factor representing the effect of a nonuniform charge distribution on the interface, and $\delta$ is now the physical gap between the reticle and dielectric layer. In practice $R_V$ and $R_{CL}$ can be measured; $t_{CL}$ can then be obtained from a measurement of pressure at a given voltage.

The first term in the expression arises from the conventional Coulomb force between the chuck electrode and the substrate. The second term arises from the J-R effect. Typically $t_d \gg t_{CL}$, so the Coulomb term is negligible compared to the J-R term. The empirical factor $\alpha$ represents the effect of the non-uniform distribution of charge on the interface surfaces. Here a value of 2.5 was assumed [5].

The J-R force depends on electrical contact between the chuck and substrate. This leads to distinctly different behavior from that of the Coulomb chuck when nonflat substrates or particles are present, as illustrated in Fig. 2(b). No clamping force is generated in the noncontacting regions. This brings into question the effectiveness of the J-R chuck for high flatness requirement applications, and is a major motivation for the present study.

**FIGURE 2.** (a) Characteristics of a J-R chuck and (b) corresponding pressure distribution with an entrapped particle.
Finite element (FE) analyses have been used to investigate the J-R performance for nonflat substrates. However, the contact requirement for J-R force generation causes a problem, because of the finite mesh of the model. Therefore, for computational convenience a finite range is assumed for the J-R force. The finite range is introduced into Eq. (4) by redefining the constant $\alpha$ as a gap dependent function, which decreases from 2.5 at zero gap to zero at a gap of 30 nm. While this finite range is introduced to facilitate convergence within the FE model, short range forces, such as van der Waals ($\propto \frac{1}{\text{gap}^3}$) and Casimir ($\propto \frac{1}{\text{gap}^4}$) exist over a comparable distance [6] and would be included in a more complete theory.

FINITE ELEMENT MODEL

In order to predict the clamping ability of Coulomb and J-R electrostatic chucks, full three-dimensional FE models were developed. Parameters were chosen to be representative for each style of chuck and the initial nonflatness of both surfaces of the reticle and of the pin surface of the chuck were based on interferometric measurements of actual chucks and reticles to provide a realistic and impartial comparison [7].

The pin chuck was modeled to have a $12 \times 12$ array of square pins, each having a side length of 2.5 mm and a height of 10 µm. The pin pitch was 12.67 mm and the coverage was 4%. The pin region was 142 mm$^2$ corresponding to the reticle quality area. The chuck was assumed to have an elastic modulus of 380 GPa and a Poisson's ratio of 0.24, which is typical for ceramic materials used in electrostatic chucks. A total thickness of 22.5 mm was used for the body of the chuck, which included a 150 µm thick dielectric for the Coulomb chuck and 2.0 mm thick dielectric for the J-R chuck.

Separate models were developed for each style of chuck and each model included the local gap-dependent pressure. All gravitational effects were ignored, and the coefficient of friction was assumed to be 0.2. The simulations were then used to predict the final flatness of the reticle patterned and backside surfaces, the final bow (or flatness) of the chuck, the final gap between the reticle and chuck, and also the pressure distribution on the backside surface of the reticle or the pressure distribution on the pins.

For each model it was assumed that the relative dielectric constant was 10. The model of the Coulomb chuck utilized an applied voltage range of 365 to 895 V, which corresponds to an average pressure (with complete chucking) of 1.0 to 6.0 kPa. The J-R model assumed a contact layer thickness of 1.0 µm and the voltage was varied from 284 to 696 V, which produces an average pressure of 1.0 to 6.0 kPa.

Results from the FE simulations are shown in Fig. 3. The remaining gap for an average pressure of 1.0 kPa is shown in Figs. 3(a) and (b) from the Coulomb and J-R models, respectively. In both cases the maximum gap is around 20 nm. For this example case, the models predict that an average pressure of 1.0 kPa is sufficient to reduce the gap from an initial value of 1.0 µm down to approximately 20 nm. At an average pressure of 6.0 kPa, the remaining gap is predicted to be negligible.

### FIGURE 3

Residual gap at 1 kPa average pressure for (a) the Coulomb chuck and (b) the J-R chuck. Note that the size of pin areas are exaggerated for display purposes.

Figures 4(a) and (b) show the final pattern surface shape of the reticle at an average pressure of 6.0 kPa; the shapes are very similar.
For these plots the applied voltage for the Coulomb and J-R cases was 895 V and 696 V, respectively. The \( p-v \) value for these surfaces is approximately 90 nm, and the \( p-v \) value within the quality area for both is just under 80 nm. Since the models predicted almost complete chucking at 1.0 kPa, the pattern surface flatness of the reticles did not change significantly between an applied average pressure of 1.0 and 6.0 kPa.

The final flatness of the backside (or chucking surface) of the reticle is shown in Figs. 5(a) and (b) for the Coulomb and J-R models, respectively, for an average pressure of 6.0 kPa. Both models predict the backside surface to have a \( p-v \) of about 90 nm and a \( p-v \) value of approximately 50 nm within the quality area. The overall shape of the contours of these plots are quite similar; however, the local distortion at or between the pins is much more apparent in the Coulomb case.

**FIGURE 4.** Reticle pattern surface after chucking with an average pressure of 6.0 kPa on a (a) Coulomb chuck and (b) J-R chuck. Both scales are in nanometers.

**FIGURE 5.** Reticle backside surface after chucking with an average pressure of 6.0 kPa on a (a) Coulomb chuck and (b) J-R chuck. Both scales are in nanometers.

Figure 6 is a plot of the remaining gap as a function of average pressure. The Coulomb chuck results in smaller gaps at lower pressure and the J-R chuck provides slightly smaller gaps at larger average pressures. Even though the Coulomb and J-R chucks have drastically different pressure dependence on gap, both are able to completely flatten the reticle against the chuck.

**SUMMARY AND CONCLUSIONS**
The governing pressure equations for Coulomb and J-R chucks were presented, and for the nominal parameters used, the J-R chuck was capable of producing significantly higher pressures for the same applied voltage in the contact (pin) regions. Due to the J-R chuck dependence on contact to initiate charge accumulation, the J-R chuck pressure is spatially nonuniform and restricted to the contacting regions. However, due to the Coulomb chuck having a spatially uniform pressure distribution, it could cause some reticle distortion between pins. A desirable attribute of a Coulomb chuck is that the pressure is not
highly dependent on gap and therefore would not change appreciably due to the presence of a particle. If relatively tall pins are required to minimize particle effects, the force in a Coulomb chuck could be significantly reduced while the pressure in a J-R chuck would change a negligible amount. However, what still needs to be determined is how a J-R chuck will perform with a particle between a pin and the backside of the reticle. Additionally, in-plane distortion of the reticle surface was not included in this study.

FIGURE 6. Summary of the gap as a function of average pressure.

The FE simulations indicated that for the example case considered, average pressure was a good predictor of final gap and flatness regardless of the chuck type. Both styles of chucks were able to pull the nonflat reticle to complete contact with the nonflat chuck with reasonable average chucking pressures.

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REFERENCES