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CHUCKING PRESSURES FOR IDEALIZED COULOMB-TYPE ELECTROSTATIC CHUCKS

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Coulomb-type electrostatic chucks are considered to be a key-technology for the next generation extreme-ultra-violet lithography. The electrostatic pressure holds the photo-mask during the fabrication process in vacuum. Different formulas appear in the literature on how to relate this electrostatic pressure to the applied voltage on the chuck electrode. We discuss the physical meaning of the corresponding formulations and also consider the implications for correct boundary conditions during finite element simulations.

1. Introduction

In order to model the forces acting in a Coulomb-type electrostatic chuck system holding a photo-mask, assume an ideal capacitor as pictured in Fig. 1. Two conducting plates are separated by the chuck dielectric with thickness d and relative permittivity ϵ_r, and a vacuum gap of size $\delta_a > 0$. Let the lower plate represent the chuck electrode which is fixed in space. The upper plate is assumed to be a rigid mask with a conducting back-side layer, which is held by a force F to ensure static equilibrium. We assume the dielectric to be perfect in the sense that no leakage current occurs; i.e. we focus in this

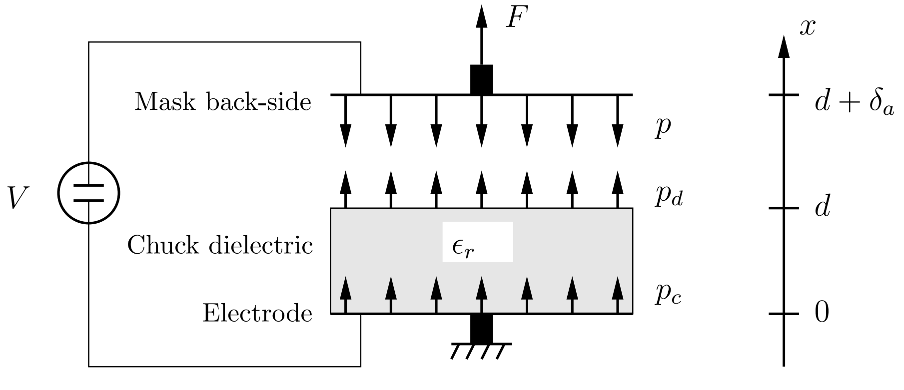

Figure 1: Schematic of electrostatic forces acting on mask back-side and chuck dielectric/-electrode when $\delta_a > 0$.

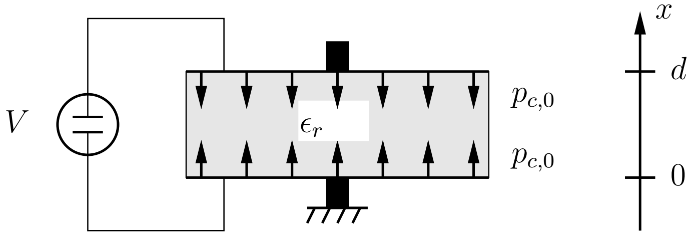

Figure 2: Schematic of electrostatic forces acting on mask back-side and chuck dielectric/-electrode during full contact.

analysis on a Coulomb-type electrostatic chuck as opposed to a Johnsen-Rahbek electrostatic chuck (see e.g. [1]). We also assume that the dielectric is rigid, homogeneous, linear and neutrally charged. We will show that due to a potential difference V between the conducting mask back-side and the chuck electrode, the following pressures are acting on the mask back-side, the top surface of the dielectric and the chuck electrode respectively:

$$p(\delta_a) = \frac{\epsilon_0 \epsilon_r^2 V^2}{2(d + \epsilon_r \delta_a)^2} \tag{1}$$

$$p_d(\delta_a) = \frac{\epsilon_0 (\epsilon_r^2 - \epsilon_r) V^2}{2(d + \epsilon_r \delta_a)^2} \tag{2}$$

$$p_c(\delta_a) = \frac{\epsilon_0 \epsilon_r V^2}{2(d + \epsilon_r \delta_a)^2} \,, \tag{3}$$

where ϵ_0 is the permittivity of free space and equal to 8.85×10^{-12} $\mathrm{C}^2/\mathrm{Nm}^2$. Recent literature commonly agrees on the use of (1) as the pressure acting on the mask back-side (see e.g.[2, p.45], [3], [4], [1], [5], [6], [7] or [8]). An early publication by [9] states (3) as the electrostatic pressure acting on the mask and chuck. We find this to be incomplete and require (2) acting on the dielectric, such that the overall electrostatic pressure acting on the chuck adds up to (1).

Consider next the situation where $F = 0$; i.e. the mask is in contact with the chuck dielectric as illustrated in Fig. 2. As we will show, the contact pressure acting at the top and bottom surface is equal to

$$p_{c,0} = p_c(0) = \frac{\epsilon_0 \epsilon_r V^2}{2d^2} \,. \tag{4}$$

This formula was established by [9] and is used for example by [10], [11], [12], [13], [14], [15], [16] and [5]. However, recent publications by [7] or [4] propose to use $p(0)$ as the chucking pressure when $\delta_a = 0$, as opposed to $p_{c,0}$ which differs by a factor ϵ_r. In the following discussion we argue that both formulations have their validity, depending on their use for example in finite element simulations.

2. ELECTROSTATIC PRESSURE CALCULATION

Let us first derive the electrostatic pressures for the different cases mentioned above. We will carry out a direct calculation via the Maxwell stress tensor (MST) and also compare the results to variations in the potential energy.

As stated in [17, p.66], the MST in the presence of a dielectric material is given by

$$\mathbf{T} = \mathbf{E} \otimes \mathbf{D} - \frac{1}{2} (\mathbf{E} \cdot \mathbf{D}) \, \mathbf{I} \,, \tag{5}$$

where $\mathbf{I}$ is the rank-2 identity. $\mathbf{E}$ is the total electrical field and $\mathbf{D} = \epsilon \mathbf{E}$ the electrical displacement, with $\epsilon = \epsilon_0 \epsilon_r$ in the linear dielectric chuck material and $\epsilon = \epsilon_0$ in vacuum. We assume that the resultant force on any volume $\mathcal{R}$ if given by

$$\mathbf{f} = \int_{\partial \mathcal{R}} \mathbf{T} \mathbf{n} \,. \tag{6}$$

Across a surface of discontinuity in $\mathbf{T}$, this will give us the traction acting on the surface as

$$[\![\mathbf{T}]\!] \mathbf{n} \,. \tag{7}$$

Here we denote the jump $[\![\mathbf{T}]\!] = \mathbf{T}^+ - \mathbf{T}^-$, where $+-$ indicate the values slightly above the surface in the $\mathbf{n}$ direction, or below the surface respectively.

Assume now a geometry as shown in Fig. 1. By employing Gauss' law, one can easily verify that the magnitude of the total electrical field is given by $\mathbf{E} = -E(x)\hat{\mathbf{x}}$, with

$$E(x) = \begin{cases} 0, & x < 0 \\ \frac{\sigma_f}{\epsilon_0 \epsilon_r}\,, & 0 < x < d \\ \frac{\sigma_f}{\epsilon_0}\,, & d < x < d + \delta_a \\ 0, & d + \delta_a < x \,, \end{cases} \tag{8}$$

where σ_f is the free surface charge density on the conducting plates. The important MST component

$$T_{xx}(x) = \begin{cases} 0, & x < 0 \\ \frac{\sigma_f^2}{2\epsilon_0 \epsilon_r}\,, & 0 < x < d \\ \frac{\sigma_f^2}{2\epsilon_0}\,, & d < x < d + \delta_a \\ 0, & d + \delta_a < x \,. \end{cases} \tag{9}$$

Since in e-chucking applications we control the potential difference rather than the surface charges, we use $V = \int_0^{d+\delta_a} E dx$ to derive

$$\sigma_f = \frac{\epsilon_0 \epsilon_r V}{d + \epsilon_r \delta_a} \,. \tag{10}$$

For the case that $\delta_a > 0$, we then get by (7),(9), and (10) the electrostatic pressure acting on the mask back-side as

$$p = T_{xx}(d+\delta_a)^- - T_{xx}(d+\delta_a)^+ = \frac{\epsilon_0 \epsilon_r^2 V^2}{2(d+\epsilon_r \delta_a)^2}\,, \tag{11}$$

which is equivalent to (1). For the pressure acting on the top-surface of the chuck dielectric

$$p_d = T_{xx}(d)^+ - T_{xx}(d)^- = \frac{\epsilon_0 (\epsilon_r^2 - \epsilon_r) V^2}{2(d+\epsilon_r \delta_a)^2}\,, \tag{12}$$

which is equivalent to (2) and

$$p_c = T_{xx}(0)^+ - T_{xx}(0)^- = \frac{\epsilon_0 \epsilon_r V^2}{2(d+\epsilon_r \delta_a)^2} \tag{13}$$

for the pressure acting on the chuck electrode as stated in (3). In a similar fashion we derive for the case $\delta_a = 0$ as pictured in Fig. 2 the pressure

$$p_{c,0} = T_{xx}(0)^+ - T_{xx}(0)^- = \frac{\epsilon_0 \epsilon_r V^2}{2d^2} \tag{14}$$

as given by (4).

Note that (1)-(4) can also be derived by considering the potential energy stored in the total system capacitance which is related to the electric field and the electric displacement. As shown for example in [18, p.192], the energy of the system [1] can be obtained by

$$W = \frac{1}{2} \int \mathbf{D} \cdot \mathbf{E}\,. \tag{15}$$

From this we find using (8) and (10) the energy per unit area as

$$w(d, \delta_a) = \frac{\epsilon_0 \epsilon_r V^2}{2\,(d+\epsilon_r \delta_a)}\,. \tag{16}$$

For the case where $L = d + \delta_a$ is fixed, we define the energy per unit area as $\hat{w}(d) = w(d, L-d)$. One can then verify that

$$p = \frac{\partial}{\partial \delta_a} w(d, \delta_a) \tag{17}$$

$$p_d = \hat{w}'(d) \tag{18}$$

$$p_c = \frac{\partial}{\partial d} w(d, \delta_a) \tag{19}$$

$$p_{c,0} = \frac{\partial}{\partial d} w(d, 0)\,, \tag{20}$$

which is equivalent to what we obtained before.

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[1] Here we refer to the energy associated with the separation of the free and bound charges, as well as the polarization of the molecules in the dielectric material.

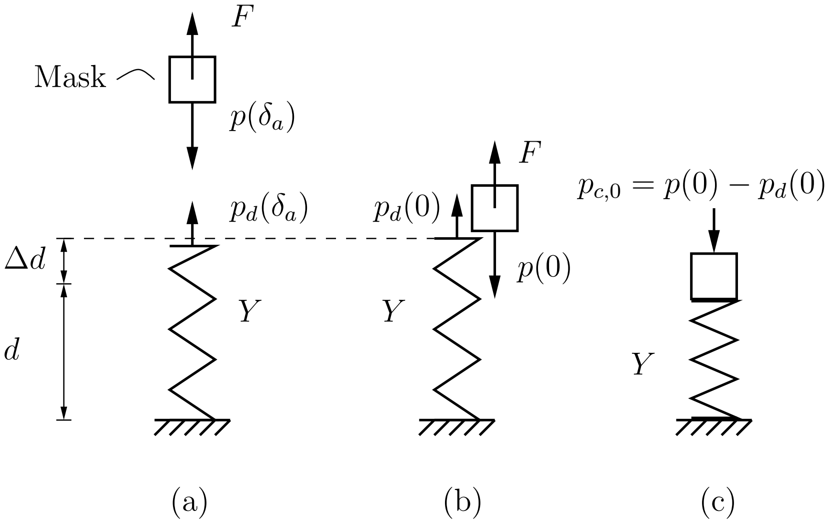

Figure 3: Schematic of elastic chuck dielectric with stiffness Y, rigid mask and pressures acting during (a) no-contact, (b) touch-down and (c) full-contact state.

3. ELASTIC CHUCK DIELECTRIC AND FINITE ELEMENT BOUNDARY CONDITIONS

We now wish to discuss the case where the mask and the chuck are in contact. As mentioned earlier, two formulas for the pressure acting on the bodies can be found in the literature, namely $p_{c,0} = \frac{\epsilon_0 \epsilon_r V^2}{2d^2}$ and $p(0) = \frac{\epsilon_0 \epsilon_r^2 V^2}{2d^2}$. In order to explain the differing factor of ϵ_r, we consider the chuck dielectric as an elastic body.

Assume an elastic dielectric layer of the chuck with Young's modulus Y. We picture three different states in Fig. 3. In Fig. 3(a) there is no contact between the mask and the chuck dielectric, the vacuum gap is δ_a, and we consider a stretch of the dielectric resulting from the pressure $p_d(\delta_a)$. [2] Assume that the mask approaches the chuck and is held by force F to ensure static equilibrium. Just before the contact is established, the stretch in the chuck dielectric is measured as Δd, which is pictured in Fig. 3(b) and referred to as the touch-down state. When $F = 0$, the chuck dielectric is compressed by the pressure $p_{c,0} = p(0) - p_d(0)$ as shown in Fig.3(c).

If we want to know the pressure that is necessary in order to release the mask from the dielectric (i.e. bring the system back to the touch-down state), we require a force $p(0)$ acting on the mask. The pressure $p(\delta_a)$ is also the total pressure acting on the chuck and the mask when there is no contact.

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[2] In Appendix A we will argue that typical stretches of the dielectric are small and that it is not necessary to account for the variation of d when calculating the electrostatic pressures.

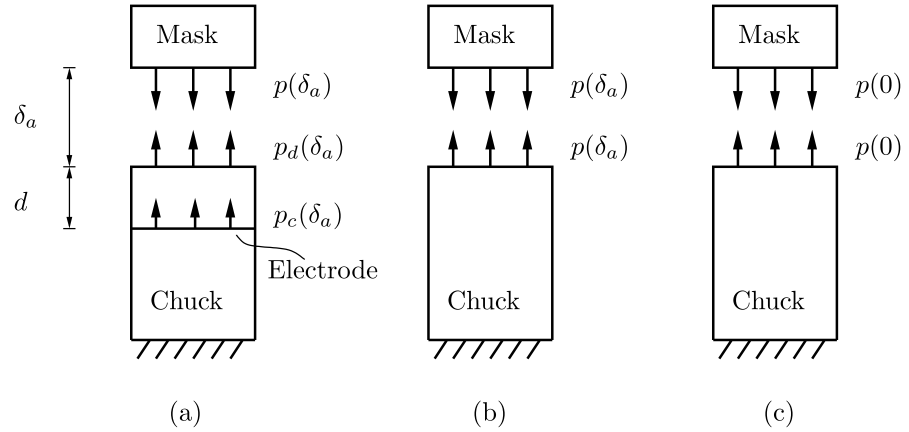

Figure 4: Loading boundary conditions for finite element simulations: (a) gap-dependant pressure on mask back-side and chuck dielectric/-electrode, (b) gap-dependant pressure on mask back-side and chuck boundary surface, (c) constant pressure approximation.

Thus it seems reasonable to use a simplified finite element model as pictured in Fig. 4(b). Here we apply a pressure p depending on the vacuum gap δ_a on the boundary surface of the chuck and mask back-side surface. This allows us to avoid the modeling of a dielectric layer with the corresponding pressures as pictured in Fig. 4(a). Furthermore, note that we can avoid a gap-dependant boundary condition formulation whenever $\delta_a/d \ll 1$ as we remark in Appendix A. As pictured in Fig. 4(c), we then apply only the constant pressure $p(0)$ on both surfaces.

4. Conclusions

We calculated the electrostatic pressures for a Coulomb-type electrostatic chuck under idealized conditions. In particular, we considered the pressures acting on the mask back-side, the chuck dielectric and -electrode and are able to explain the differences in the literature concerning the relation between the electrostatic pressure and the applied voltage. Finally, the implications for correct boundary conditions as used for example in finite element simulations are noted.

5. Acknowledgements

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APPENDIX A. APPROXIMATIONS

We briefly justify the idealization of a rigid dielectric material for the electrostatic pressure calculation and discuss the validity of a constant pressure approximation as a further simplification as often used for example in finite element simulations.

In order to estimate the sensitivity of the electrostatic pressure versus the dielectric thickness, we linearize (1) at $\delta_a = 0$. By varying d, we obtain the estimate

$$\left|\frac{\Delta p}{p}\right| = 2\left|\frac{\Delta d}{d}\right| . \tag{21}$$

Consider a numerical example, where the mask and chuck are just in contact; i.e. $\delta_a = 0$. If we assume a typical dielectric constant $\epsilon_r = 4$, and an electrostatic pressure $p = 15$ kPa, we obtain by (2) a tensile force on the dielectric $p_d = 11$ kPa. Let us assume the Young's modulus of the material to be $Y = 90$ GPa. By taking the ratio, we estimate the relative change in the dielectric thickness as $|\Delta d/d| = p_d/Y = 10^{-7}$, and then by (21), we obtain a relative change in the pressure of $|\Delta p/p| = 2 \cdot 10^{-7}$. This is negligibly small and thus justifies the assumption of a constant dielectric thickness for the given example.

Finally note the sensitivity of the electrostatic pressure calculation via (1) on the air gap δ_a. By varying the air gap δ_a, we obtain

$$\left|\frac{\Delta p}{p}\right| = 2\epsilon_r\left|\frac{\Delta \delta_a}{d}\right| . \tag{22}$$

In e-chucking applications, the peak-to-valley in the non-flatness of the mask back-side corresponds to $\Delta\delta_a$ in the idealized model. From (22) we see that whenever $|\Delta\delta_a/d| \ll 1$, the resulting pressure variation is negligible. Thus, as a further simplification of the model as proposed in Section 3, it is reasonable to assume a constant pressure of magnitude

$$p = \frac{\epsilon_0\epsilon_r^2 V^2}{2d^2} \tag{23}$$

acting on the mask back-side and the chuck, whenever $|\Delta\delta_a/d| \ll 1$. This was also observed in [19], where small ratios $|\Delta\delta_a/d|$ would not alter the prediction of the mask deformation when comparing a gap dependant pressure formulation via (1) and the constant pressure approximation (23).