Multiphysics Simulation of Conjugated Heat Transfer and Electric Field on Application of Electrostatic Chucks (ESCs) Using 3D-2D Model Coupling

Kuo-Chan Hsu[1]， Chih-Hung Li[1]， Jaw-Yen Yang[1,2]
Jian-Zhang Chen[1]， Jeng-Shian Chang[1]

[1]Institute of Applied Mechanics, National Taiwan University, Taiwan (R.O.C)
[2]Center for Advanced Study in Theoretical Sciences, National Taiwan University, Taiwan (R.O.C)

Outline

i. Overview of Electrostatic Chucks (ESCs)

ii. Why is Multiphysics?

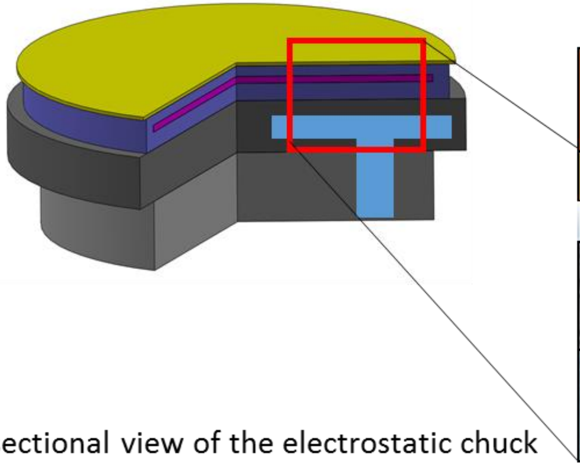
iii. Boundary Conditions
    a) Electric field model
    b) Conjugated heat transfer model

iv. Result of Simulation
    a) Electric field model
    b) Conjugated heat transfer model

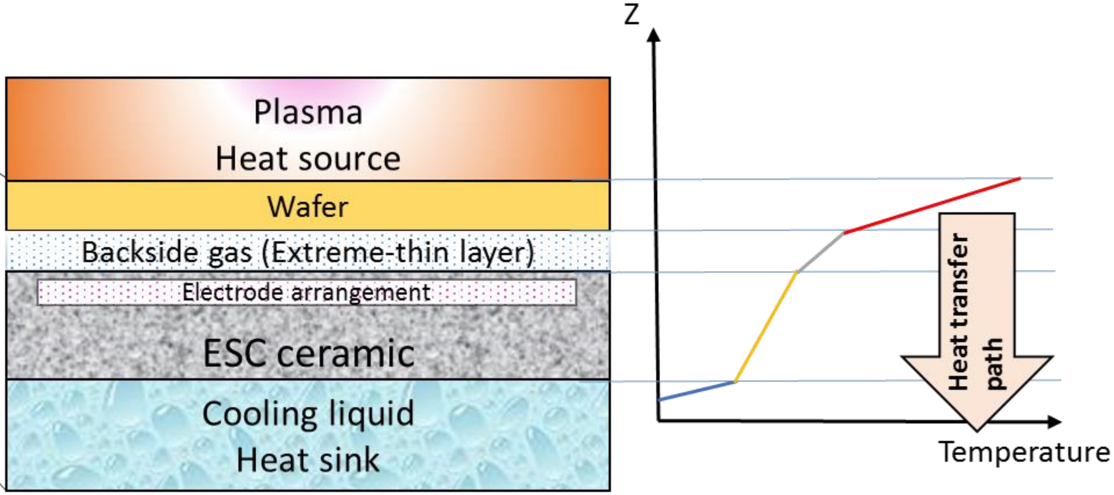
vi. Conclusion

Simulation model

Overview



Cross-sectional view of the electrostatic chuck



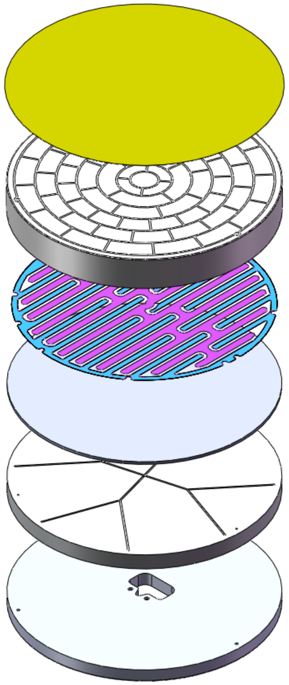
The main thermal resistances in the heat path are the ceramic and the transition from the ceramic to the cooling liquid.

Thermal energy is transferred to the wafer surrounding through ion bombardment, and the chuck is required to remove large amounts of heat from the wafer while maintaining a stable and uniform temperature.

	AlN	Al_2O_3	Al6061	Si
Thermal Conductivity @20$[^W/_{mK}]$	180.0	35	167.0	150.0
Coefficient of thermal expansion$[^{10^{-6}}/_{°C}]$	6.8	8.1	23.0	5.0

Ref:1.Four Decades of Research on Thermal Contact, Gap,and Joint Resistance in Microelectronics Yovanovich, M.M. Components and Packaging Technologies, IEEE Transactions on Volume: 28, Issue: 2 , 2005
2.Microscopic approach to an equation for the heat flow between wafer and E-chuck, M Klick, M Bernt - Journal of Vacuum Science & Technology B, 2006
3.J.YOO et al., Proceeding of International Conference on Electrical Machines and Systems (2007)

Multiphysics



Exploded drawing of the ESC

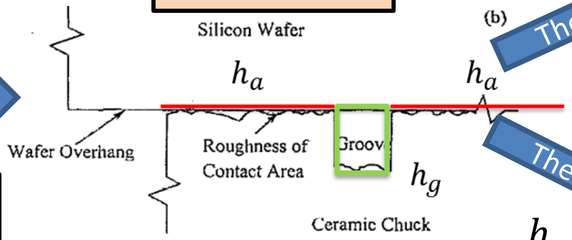
Groove for Helium

Electrode

Groove for water

Physics

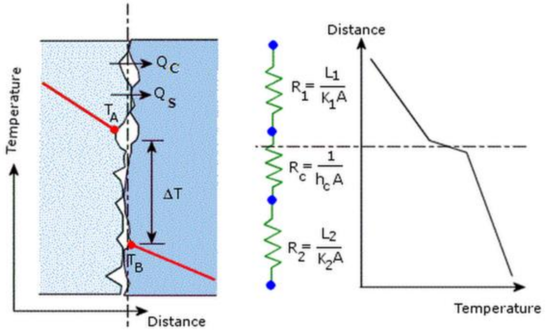
Heat transfer



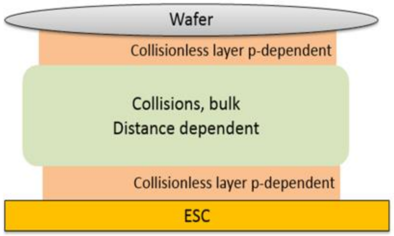
h_a Theory

h_g Theory

Cooper-Mikic-Yovanovich Correlation

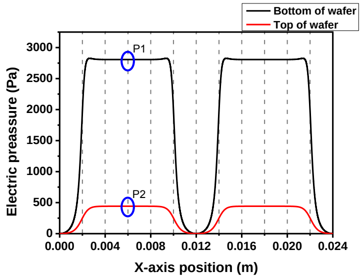


Principal Dependencies of the Wafer Temperature



Physics

Electrostatic force



Theory

Maxwell's stress tensor

$$T_{ij} = \varepsilon E_i E_j - \frac{\varepsilon}{2}(E_k E_k)\delta_{ij} = \begin{bmatrix} \frac{\varepsilon}{2}(E_x^2 - E_y^2) & \varepsilon E_x E_y \\ \varepsilon E_x E_y & \frac{\varepsilon}{2}(E_y^2 - E_x^2) \end{bmatrix}$$

Physics

Fluid dynamics

Theory

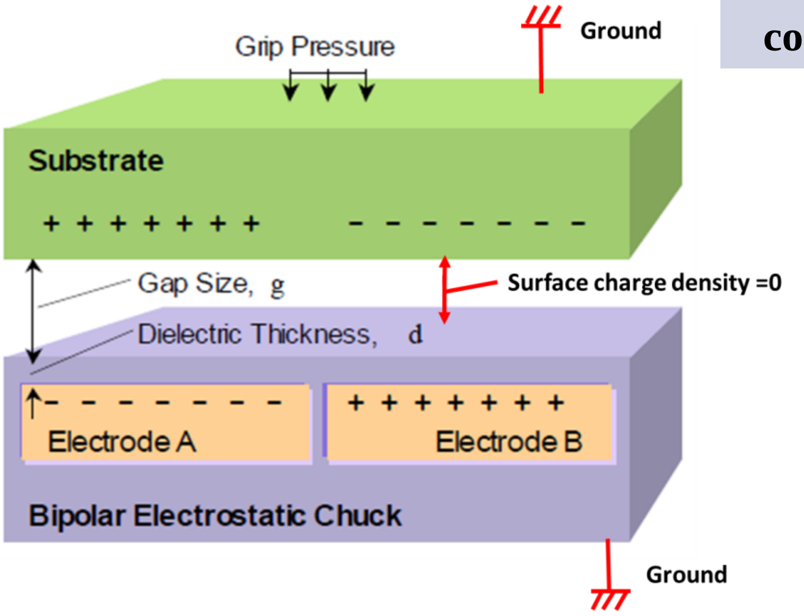
Navier-Stokes Equation

Navier–Stokes equations *(general)*

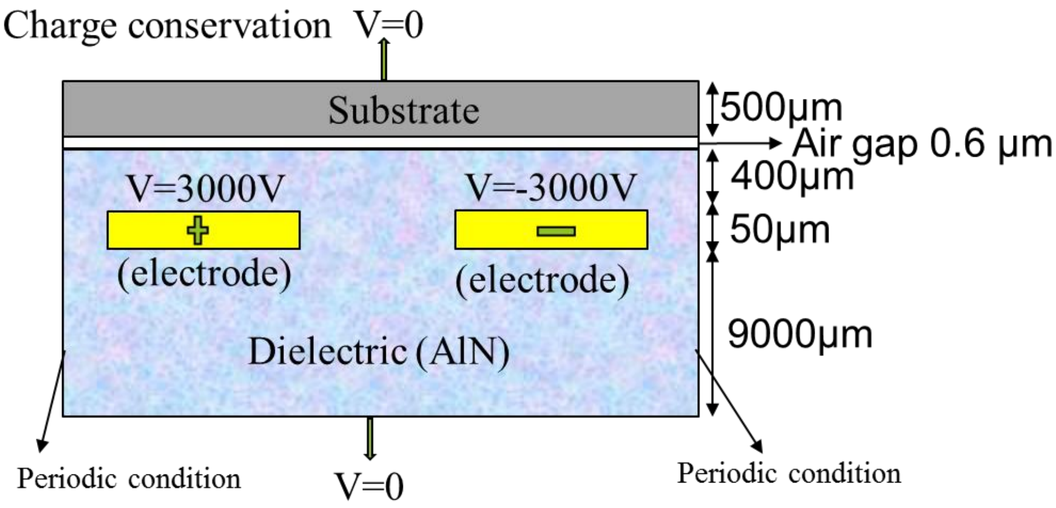
$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbf{T} + \mathbf{f}$$

Boundary Conditions

	Silicon	AlN	Al_2O_3	Air
Dielectric constant	11.7	9	9	1

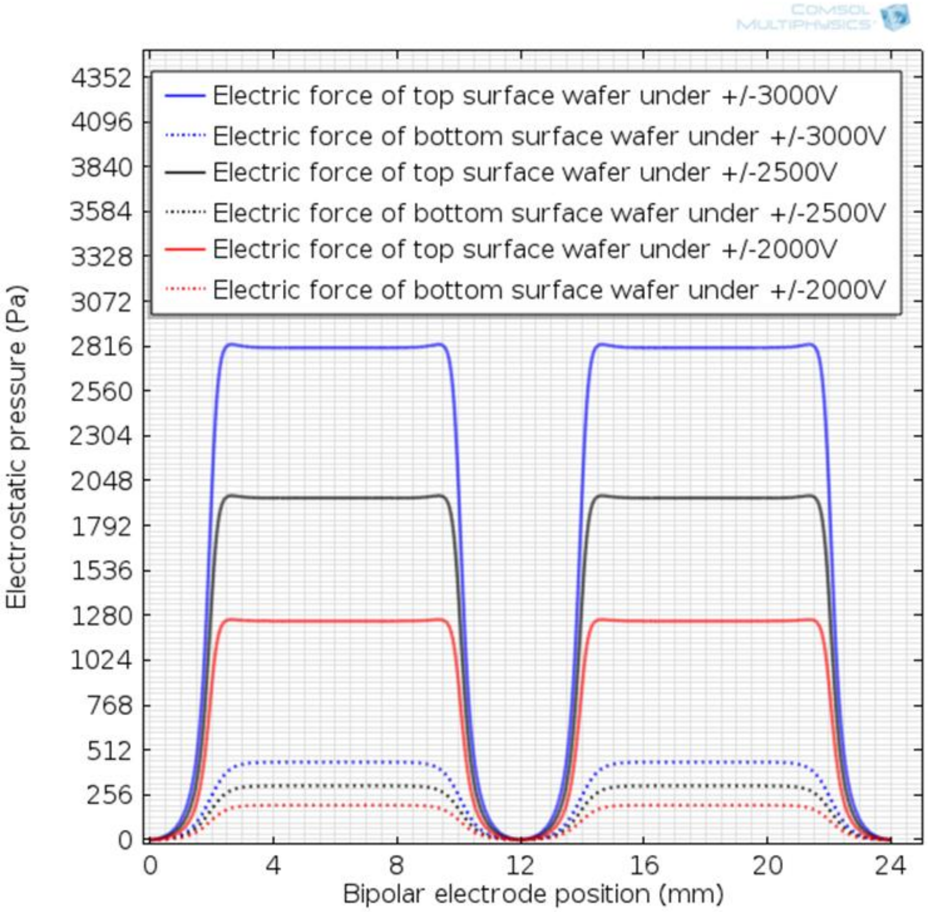


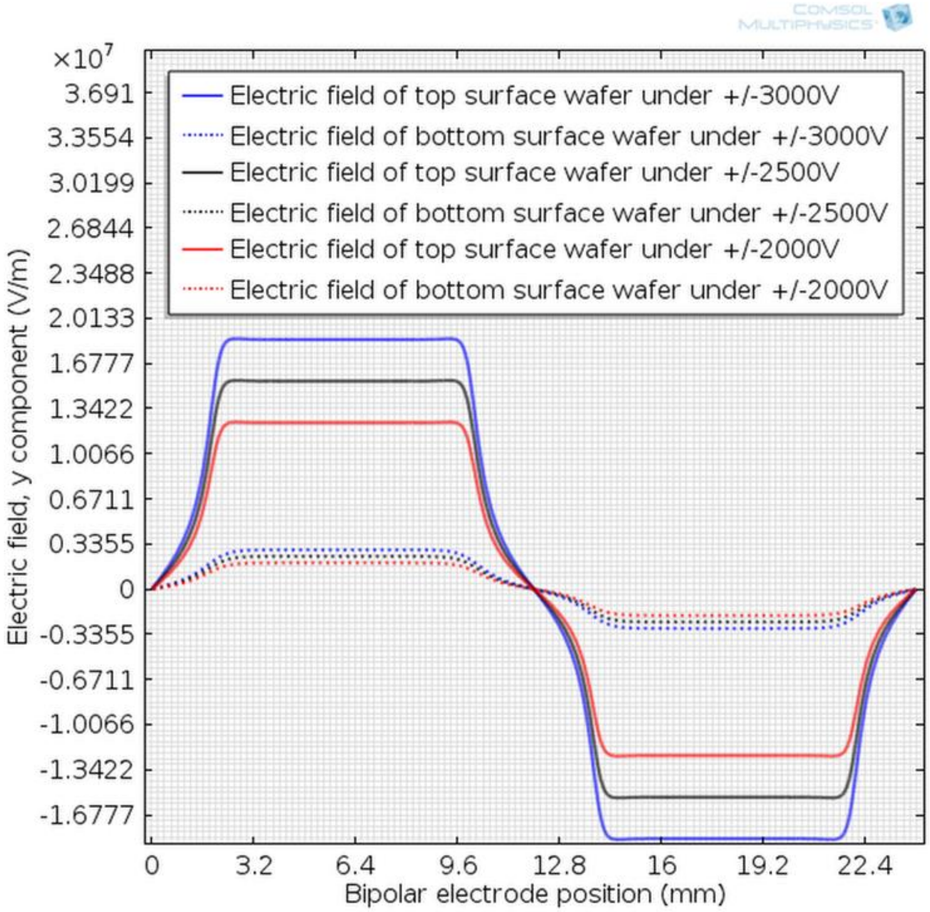
Boundary conditions setting up



Geometry of electrode pairs (Bipolar)

Result for Electric Field





Excerpt from the Proceedings of the 2014 COMSOL Conference in Shanghai

Boundary Conditions

☐ Assumptions:

i. Stationary state
ii. Thermal insulation in the chamber
iii. Neglect the heat radiation effect
iv. Uniform heat source to the wafer from plasma
v. Neglect the heat of chemical reaction on wafers

Cooper-Mikic-Yovanovich Correlation

$$h_s = 1.25\,k\,\frac{m_{asp}}{\sigma_{asp}}\left(\frac{p}{H_c}\right)^{0.95}$$

Maxwell's stress tensor

$$T_{ij} = \varepsilon E_i E_j - \frac{\varepsilon}{2}(E_k E_k)\delta_{ij} = \begin{bmatrix} \frac{\varepsilon}{2}(E_x^2 - E_y^2) & \varepsilon E_x E_y \\ \varepsilon E_x E_y & \frac{\varepsilon}{2}(E_y^2 - E_x^2) \end{bmatrix}$$

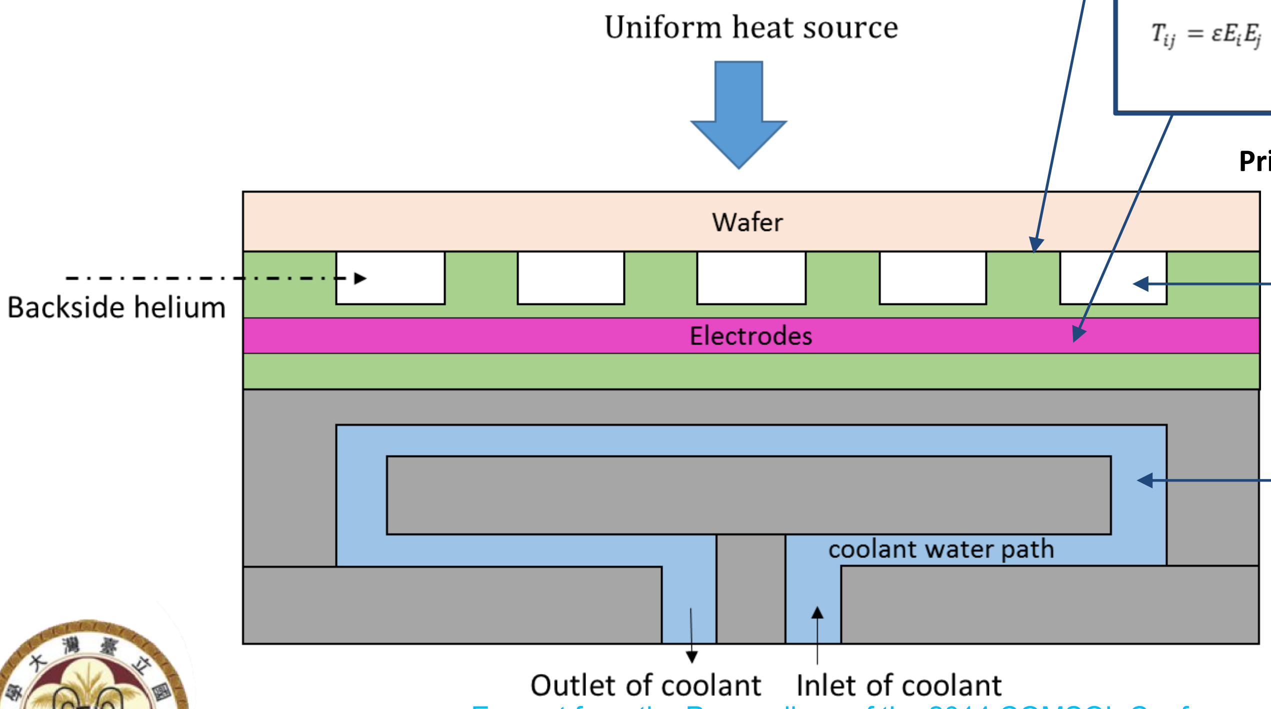
Principal Dependencies of the Wafer Temperature

$$h_f = \frac{q}{A\Delta T} = \left(\frac{C}{p\alpha_a} + \frac{d}{\kappa} + \frac{C}{p\alpha_b}\right)^{-1}$$

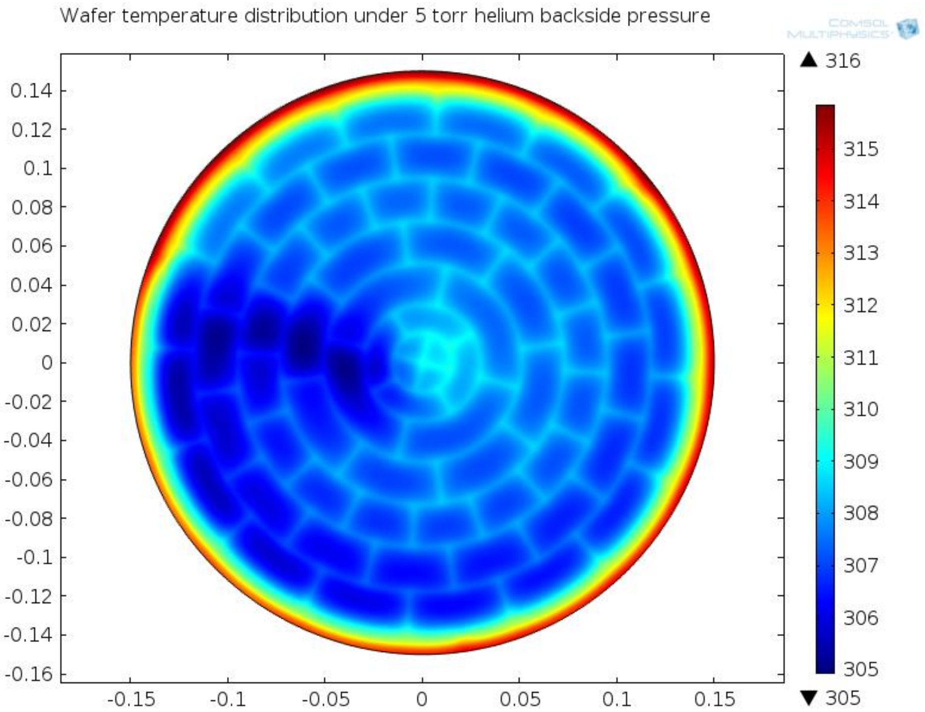
Navier-Stokes Equation

Navier–Stokes equations *(general)*

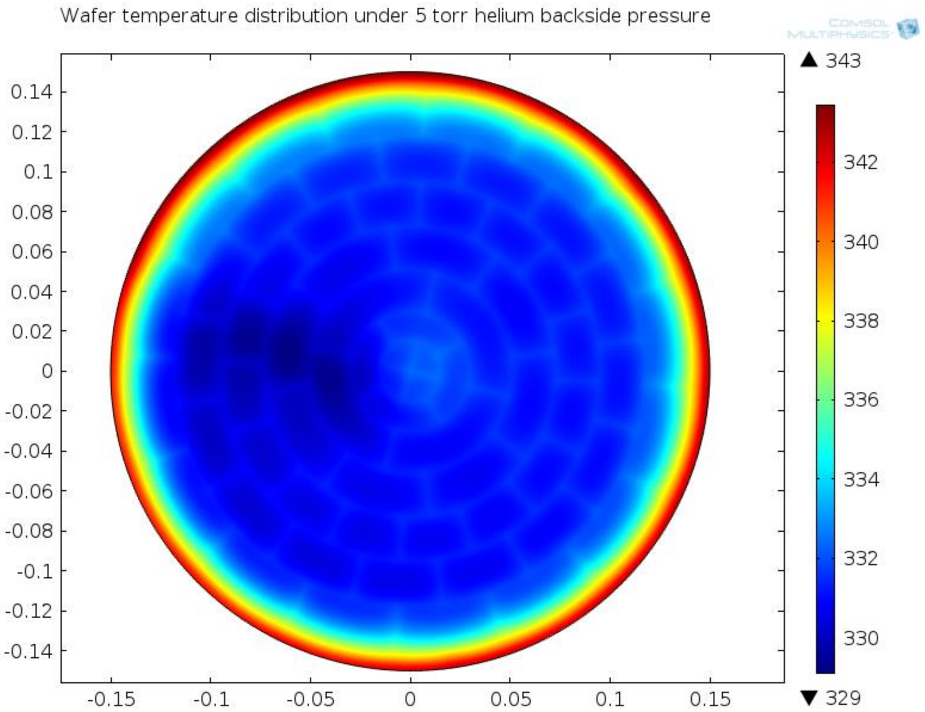
$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbf{T} + \mathbf{f}$$



Simulation Result



AlN ceramic body

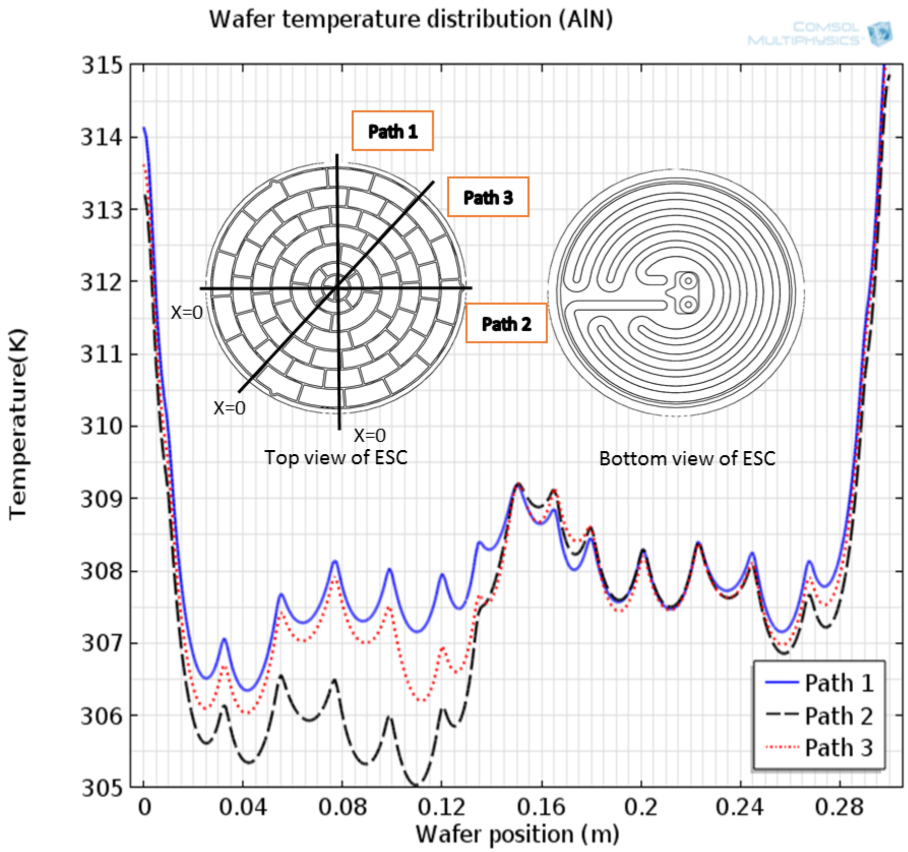


Al_2O_3 ceramic body

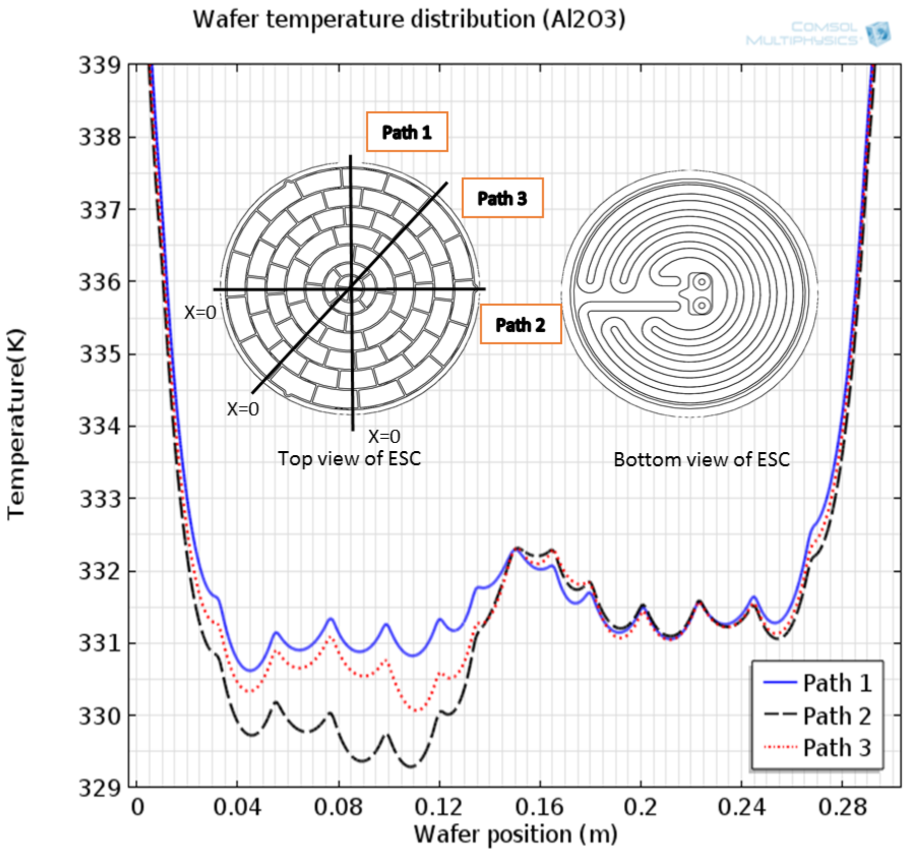
From the result of simulation, the deep blue is near to the cooling inlet. It means the temperature distribution largely depends on the geometry of cooling liquid. Due to the high thermal conductivity for AlN, most of the heat goes through ceramic material and is transferred to cooling liquid.

Excerpt from the Proceedings of the 2014 COMSOL Conference in Shanghai

Simulation Result



AlN ceramic body



Al_2O_3 ceramic body

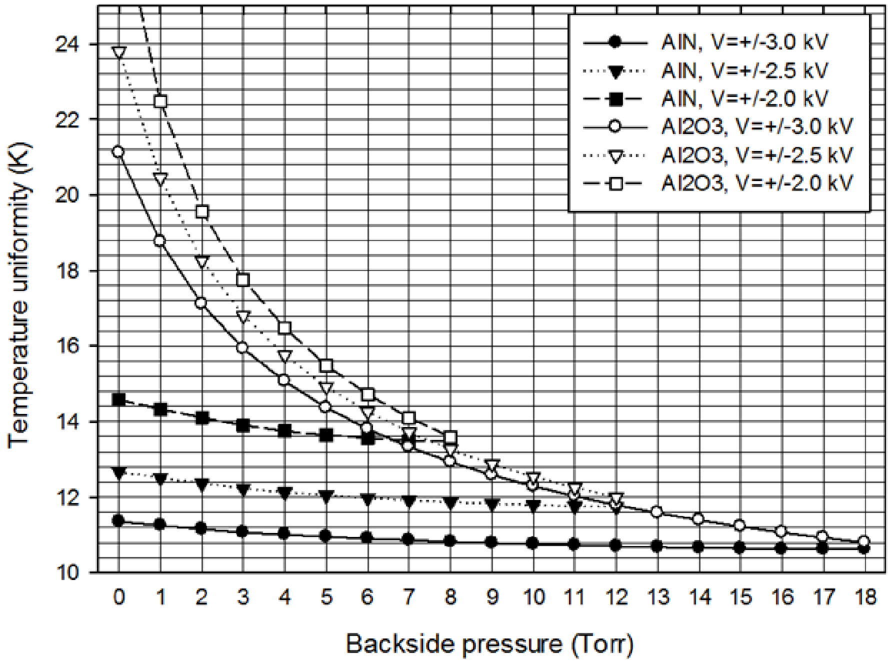
Excerpt from the Proceedings of the 2014 COMSOL Conference in Shanghai

Simulation Result

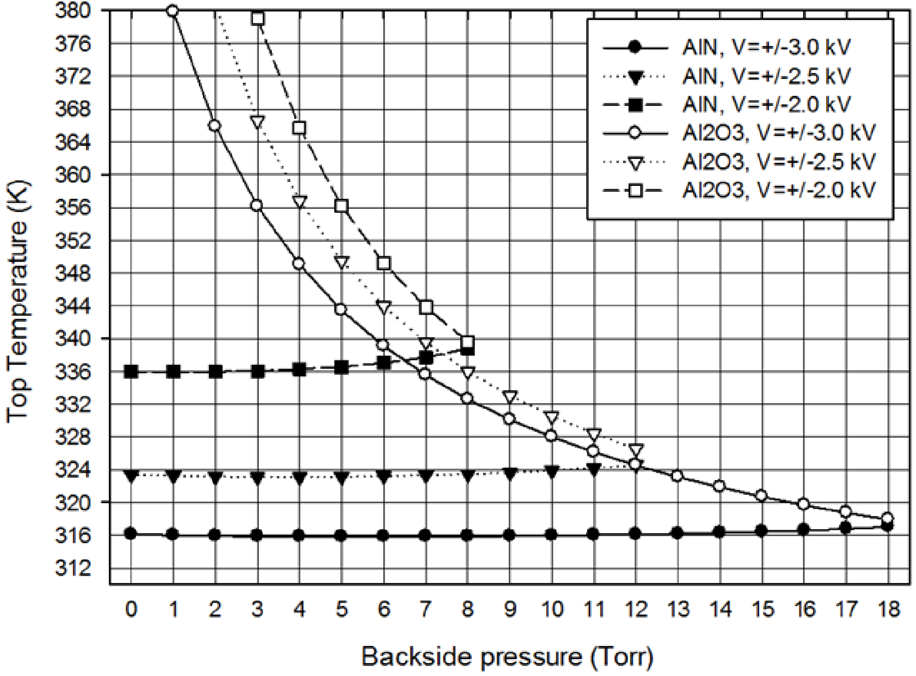
For Al_2O_3 ceramic, most of the heat energy is transferred to backside helium due to low thermal conductivity.

For AlN ceramic, most of the heat energy is transferred to cooling liquid due to high thermal conductivity.

Temperature uniformity



Top Temperature



Excerpt from the Proceedings of the 2014 COMSOL Conference in Shanghai

Conclusion

I. The AlN ceramic body significantly reduces the wafer temperature and non-uniformity than $\mathrm{Al_2O_3}$ does.

II. The non-symmetrical temperature distribution mainly results from the geometric design of cooling water channel.

III. The electrostatic voltage is a principal factor of the wafer temperature and the distribution.

IV. The top temperature slightly increases as backside pressure due to the less contact force of ESCs to the wafer.

V. Relationship between the electrostatic force and potential voltage is built up.

Thank You
for Your Attention!

Kuo-Chan Hsu
Aerodynamics Design & Analysis Laboratory
R007, Institute of Applied Mechanics, National Taiwan University
No.1, Sec.4, Roosevelt Road, Taipei 106, Taiwan
Email: r02543025@ntu.edu.tw

The authors gratefully acknowledge the funding by National Chung-Shan Institute of Science & Technology (NCSIST) and assistance of Leading Precision Inc. (LPI).