TEMPERATURE CONTROL OF ESC UNDER COLD WAFER CHUCKING DISTURBANCE USING MODERN TWO DEGREES-OF-FREEDOM CONTROLLER DESIGN

*Jiaxuan Zhang, Yuanzhe Zhao, Zhiyuan Liu, Boyang Mu, and Kai Zhang**

AI Engineering, Advanced Micro-Fabrication Equipment Inc. China (AMEC), Shanghai, China

*Corresponding Author's Email: KaiZhang1@amecnsh.com

ABSTRACT

Etching in semiconductor manufacturing requires precise temperature control of the electrostatic chuck (ESC) to ensure process reproducibility. The cold-chucking procedure, where a low-temperature wafer is clamped onto a heated ESC, induces temperature fluctuations that degrade control performance. This paper proposes a two degrees-of-freedom control strategy that estimates and compensates for cold-chucking as an external unmeasurable load. A simplified first-order-plus-time-delay (FOPTD) model of the ESC is derived, and a robust observer is designed. Our simulations shows the proposed method effectively suppresses temperature fluctuations, enhances process stability and throughput, and ensures robustness in the presence of parametric uncertainties.

INTRODUCTION

Etching is a key step in semiconductor manufacturing, transferring nanoscale patterns onto wafers by precise material removal [1]. Electrostatic Chucking (ESC) is critical in this process, clamping the wafer electrostatically (known as *chucking*) under vacuum and regulating temperature to support reactions. A typical ESC includes a ceramic chuck with electrodes, backside helium gas supply, coolant channels, and heaters [2]. The electrodes and helium enable clamping, while coolant and heaters regulate temperature, monitored in real time by sensors.

Stable temperature control is essential since variations can shift etch rates, leave byproducts, harming consistency and throughput [3]. However, temperature stability during etching is challenging. A particular situation is *cold-chucking*, where a low-temperature wafer contacts the heated ESC, causing large temperature variation. A practical solution is to wait for wafer warm-up before chucking, but it wastes time and reduces throughput.

Besides normal feedback control, feedforward control can be used to mitigate such disturbance. But the performance of feedforward control highly depends on the model accuracy and unmeasurable factors like wafer initial temperature affects the thermal impact of cold-chucking. These factors making accurate modelling difficult.

This paper proposes a modern two degrees-of-freedom controller approach [4], to improve the temperature performance of ESC under cold wafer chucking disturbance. This technique estimates and suppresses the thermal disturbance in real time, overcoming the need for a precise model of wafer.

The rest of the paper will go detail into the control-oriented ESC thermal dynamics modelling and the design of modern two degrees-of-freedom controller in our case. Simulation results will also be provided to show the effectiveness of the proposed method.

PROCESS MODELLING

Figure 1 shows a sketch picture of a simplified cross-section version of ESC structure abstracted from [2] [3]. The yellow part denotes the ESC and the blue part denotes the wafer. The heater is colored in red, which is the control input of our system. The coolant channel is colored in green, which cannot be controlled in our system.

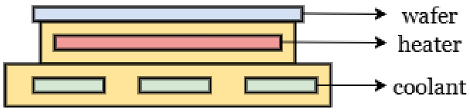

Figure 1: Simplified ESC Structure with Wafer. 1) ESC (in yellow), 2) heater (in red), 3) coolant channel (in green), 4) wafer (in blue)

Remark: This paper considers single-zone heater. The proposed method can be extended to multi-zone designs.

Exhaustive thermodynamic modeling of ESC involves complex partial differential equations (PDEs), which are often too superfluous for controller synthesis. We construct a low-order control-oriented resistance-capacity (RC) model [4] by firstly making the following assumptions based on real ESC operation conditions.

Assumption: 1) Only thermal conduction effect are considered. Heat transfer via radiation and convection are neglected. 2) The ESC is treated as thermally isolated except for heater, chiller and wafer. 3) The wafer is treated as thermally isolated except for ESC. 4) The coolant temperature is assumed to remain constant throughout the process (Without loss of generality, assume 0°C).

Figure 2 simplifies Figure 1 for heat flow analysis.

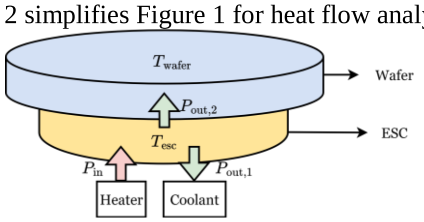

Figure 2: Simplified Heat Flow Graph of ESC

From Figure 2, an RC model can be established:

$$C_{\text{esc}}\frac{dT_{\text{esc}}}{dt}=\begin{cases}P_{\text{in}}-P_{\text{out},1} & \text{(if no chucking)}\\ P_{\text{in}}-P_{\text{out},1}-P_{\text{out},2} & \text{(if chucking)}\end{cases} \tag{1}$$

Where T_{esc} denotes ESC temperature, C_{esc} denotes the thermal capacity of ESC. P_{in}, $P_{\text{out},1}$, $P_{\text{out},2}$ denotes the heat flow from heater to ESC, from ESC to coolant channel and from ESC to wafer, respectively.

Denote the heater power as u, we obtain:

$$P_{\text{in}}=u;P_{\text{out},1}=\frac{T_{\text{esc}}}{R_1};P_{\text{out},2}=\frac{T_{\text{esc}}-T_{\text{wafer}}}{R_2} \tag{2}$$

Where R_1, R_2denotes the thermal resistance between ESC and coolant, between ESC and wafer, respectively.

When no chucking happen, the following relation can be obtained by combining equations (1) and (2).

$$C_{\text{esc}}\frac{dT_{\text{esc}}}{dt}=u-\frac{T_{\text{esc}}}{R_1} \tag{3}$$

When chucking happen, equation (4) can be obtained.

$$C_{\text{esc}}\frac{dT_{\text{esc}}}{dt}=u-\frac{T_{\text{esc}}}{R_1}-\frac{T_{\text{esc}}-T_{\text{wafer}}}{R_2}=(u+d)-\frac{T_{\text{esc}}}{R_1} \tag{4}$$

Where $d=-(T_{\text{esc}}-T_{\text{wafer}})/R_2$.

Assume $T_{esc}=0$ at $t=0$, equation (5) transform model to frequency domain.

$$T_{\text{esc}}(s)=\frac{K_{p_0}}{T_{p_0}s+1}\big(U(s)+D(s)\big) \tag{5}$$

Where $K_{p_0}=R_1$ and $T_{p_0}=C_{esc}R_1$.

For better approximation, we introduce system delay to imitate the effects of its internal thermal resistance caused by complex material composition as follows:

$$T_{\text{wafer}}(s)=\frac{K_{p_0}}{T_{p_0}s+1}e^{-\tau_0 s}\big(U(s)+D(s)\big) \tag{6}$$

Remark: equation (6) implies that the disturbance and the system input share the same time delay. More complex scenarios can be analyzed with the similar method.

Similarly, the wafer temperature can be modeled as:

$$C_{\text{wafer}}\frac{dT_{\text{wafer}}}{dt}=\frac{T_{\text{esc}}-T_{\text{wafer}}}{R_2} \tag{7}$$

CONTROLLER DESIGN

Inspired by [4], a two degrees-of-freedom controller utilizing linear frequency-domain disturbance estimator is proposed to improve the temperature control performance of ESC under cold wafer chucking. Figure 3 shows the structure, where $G_p(s)$, $G_n(s)$, $C(s)$, $Q(s)$ denotes the true plant, the nominal plant (the plant model assumed by the engineer), the feedback controller and estimator, respectively.

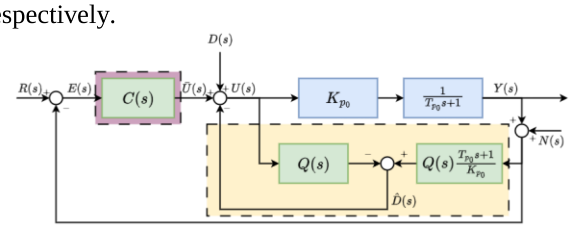

Figure 3: Two Degrees-of-Freedom Control Structure

$Q(s)$ is the crucial parameter. For servo system in [4], the design of Q(s) does not consider the effect of system delay. Inspired by [6], for system with time delay, equation (8) shows the used form of $Q(s)$.

$$Q(s)=\frac{1}{(T_q s+1)^m}e^{-\tau s} \tag{8}$$

Where τ equals to the nominal time delay in $G_n(s)$, and $m\in\mathcal{Z}^+$is an integer denotes the order of the $Q(s)$.

Assume $G_n(s)=G_p(s)$, equation (9) represents the input-output relations of the inner-loop.

$$\begin{aligned}Y(s)=G_p(s)\big(1-Q(s)\big)D(s)+G_p(s)\bar{U}(s)\\ -G_p(s)Q(s)G_n^{-1}(s)N(s)\end{aligned} \tag{9}$$

From [4] and equation (9), we can summarize the following design rules for performance.

Design Rules: : 1) For ω such that $D(j\omega)$ rejection is important, $Q(j\omega)$ should close to 1; 2) For ω such that $N(j\omega)$ is large, $Q(j\omega)$ should be small; 3) A higher order $Q(s)$ will always be superior to a lower order $Q(s)$

SIMULATION RESULT

This section presents numerical simulations to verify the effectiveness and robustness of the proposed method.

Consider additive uncertainties $G_p(s)=G_n(s)(1+\Delta(s))$ with $\Delta(s)$ stable. Specifically, three types of parametric uncertainties of FOPTD systems:

1) Process-gain uncertainties: ΔK_p

$$\begin{aligned}G_p(s)&=\frac{K_{p_0}+\Delta K_p}{T_{p_0}s+1}e^{-\tau_0 s}\\ \Rightarrow\Delta(s)&=\frac{\Delta K_p}{K_{p_0}}\end{aligned} \tag{10}$$

2) Time-constant uncertainties: ΔT_p

$$\begin{aligned}G_p(s)&=\frac{K_{p_0}}{(T_{p_0}+\Delta T_p)s+1}e^{-\tau_0 s}\\ \Rightarrow\Delta(s)&=\frac{-\Delta T_p}{(T_{p_0}+\Delta T_p)s+1}\end{aligned} \tag{11}$$

3) Time-Delay uncertainties: $\Delta\tau$

$$\begin{aligned}G_p(s)&=\frac{K_{p_0}}{T_{p_0}s+1}e^{-(\tau_0+\Delta\tau)s}\\ \Rightarrow\Delta(s)&=(e^{\Delta\tau s}-1)\end{aligned} \tag{12}$$

Remark: This paper considers above uncertainties. In practice, more complex uncertainties may exist [7].

TABLE I. shows the FOPTD model parameters and their uncertain range considered in the simulation.

TABLE I. SIMULATION PARAMETERS

Parameters	***Uncertainties***
$K_{p_0}=1$	$\Delta K_p\in[-0.5,0.5]$
$T_{p_0}=40$	$\Delta T_p\in[-10,10]$
$\tau_0=1$	$\Delta\tau\in[-0.5,0.5]$

This yields the FOPTD ESC model in equation

$$Y(s)=\begin{cases}\dfrac{1}{40s+1}e^{-s}U(s) & \text{(if no chucking)}\\ \dfrac{1}{40s+1}e^{-s}(U(s)+D(s)) & \text{(if chucking)}\end{cases}$$

A well-tuned PI controller as follows is designed [8]:

$$C(s)=6.67+0.279/s$$

The following $Q(s)$ is designed for cold-chucking:

$$Q(s)=\frac{1}{(0.5s+1)^2}e^{-s}$$

Result of Control Performance and Robustness

Figure 4 and Figure 5 shows the simulation results. In the simulations, the cold-chucking happens at 100s.

Figure 4 is control performance result. Compared to the PI-only contro l, the proposed method significantly reduces undershoot and responds faster.

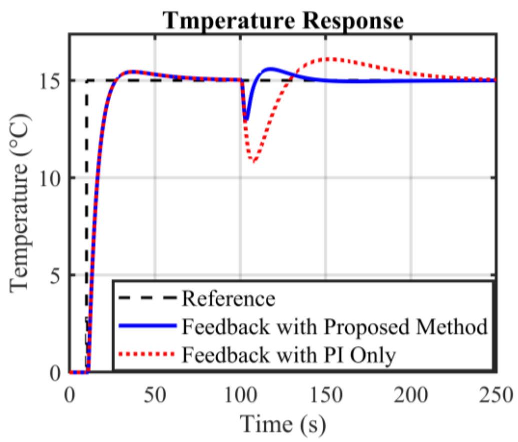

Figure 4: Result of Control Performance

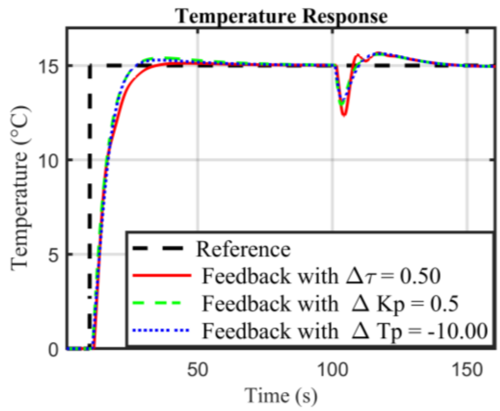

Figure 5: Result of Robustness

Figure 5 shows the robustness result. It can be observed that the proposed controller ensures robustness under the parametric uncertainties discussed above. Robustness for more general uncertainties can also be analyzed and verified by utilizing the method in [8]

CONCLUSION

Stable temperature control of ESC is pivotal for guarantee etching result and production throughput. This paper proposes a two degrees-of-freedom controller utilizing linear frequency-domain disturbance estimator to mitigate the thermal effect of cold-chucking. The core parameter is designed via frequency-domain analysis to balance performance and robustness. The time-domain simulations demonstrate that the proposed method effectively suppresses the temperature variation and ensures robustness under parametric uncertainties. The proposed approach can also be extended as an effective solution to other semiconductor manufacturing processes—such as chemical vapor deposition and rapid thermal processing—where unmeasurable load disturbances pose critical challenges to thermal and production performance.

REFERENCES

[1] Edgar, T. F., Butler, S. W., Campbell, W. J., Pfeiffer, C., Bode, C., Hwang, S. B., ... & Hahn, J. (2000). Automatic control in microelectronics manufacturing: Practices, challenges, and possibilities. Automatica, 36(11), 1567-1603.

[2] Nangoy, R., & Lubomirsky, D. (2017). U.S. Patent No. 9,681,497. Washington, DC: U.S. Patent and Trademark Office.

[3] Zhang, T., Zaninovich, J. J., & Egley, F. (2019). U.S. Patent No. 10,509,425. Washington, DC: U.S. Patent and Trademark Office.

[4] Umeno T, Hori Y. Robust speed control of DC servomotors using modern two degrees-of-freedom controller design[J]. IEEE Transactions on industrial electronics, 2002, 38(5): 363-368.

[5] Gwerder, M., Lehmann, B., Tödtli, J., Dorer, V., & Renggli, F. (2008). Control of thermally-activated building systems (TABS). Applied energy, 85(7), 565-581.

[6] Li, S., Yang, J., Chen, W. H., & Chen, X. (2016). Disturbance observer-based control: methods and applications. CRC press.

[7] Zhang, K., Scorletti, G., Ichchou, M. N., & Mieyeville, F. (2014). Robust active vibration control of piezoelectric flexible structures using deterministic and probabilistic analysis. Journal of Intelligent Material Systems and Structures, 25(6), 665-679.

[8] Ang, K. H., Chong, G., & Li, Y. (2005). PID control system analysis, design, and technology. IEEE transactions on control systems technology, 13(4), 559-576.