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ROBUST NONLINEAR CONTROL OF A RAPID THERMAL PROCESSOR

John S. Baras and Nital S. Patel

Dept. of Electrical Engineering and Institute for Systems Research

University of Maryland, College Park, MD 20742

baras@isr.umd.edu   nsp@isr.umd.edu

This paper presents application of robust multivariable nonlinear control to the temperature control problem for rapid thermal processing systems. The controller designed achieves good tracking and temperature uniformity for a wide range of processing conditions.

INTRODUCTION

Rapid thermal processing (RTP) is emerging as a significant single-wafer processing technology. Moshlehi (1), demonstrated the viability of RTP for most of the thermal fabrication steps required in sub-half-micron CMOS technologies. The short processing times enables one to meet the reduced thermal budgets for large wafers packed with high density circuitry. One of the main issues in RTP technology has been that of temperature uniformity. It is critical to maintain a uniform temperature profile across the wafer during thermal transients and steady state to avoid generating slip dislocations and to ensure process uniformity.

In this paper, we present some results on application of robust multivariable nonlinear control to the RTP temperature control problem. The controller is designed to be robust to possible variations in the wafer emissivity, as well as to variations in the chamber wall temperature. These factors affect the process dynamics, and could lead to instability, as well as to performance degradations. We employ the reduced order model obtained by (2) based on a RTP system presented in (3). In the results to be presented, we will not go into the issue of the temperature sensors, although sensors form an integral part of any control scheme. It is widely recognized that accurate sensors are a prerequisite for the success of any RTP system. It is perhaps based on this fact that most model based control strategies for RTP assume that one has good sensors (4), (5).

THE RTP MODEL

The RTP system under consideration is designed for low pressure CVD of polysilicon. The system has 3 lamp zones, and the temperature is measured at 4 points along the wafer radius, at radial distances of 2.58cm, 5.47cm, 7.22cm, and 7.6cm

from the wafer center. The last temperature measurement corresponds to the edge of the wafer (wafer radius 7.6cm). A complete description of the system can be found in (2). We will work with the following model,

$$\dot{T}_k = \kappa \sum_{j=1}^{4} B_{k,j} T_j + E_w(\epsilon(T_c^4 - T_k^4) + q(r_k)^T \cdot u), \quad k = 1, 2, 3 \qquad [1]$$

$$0 = -\sum_{j=1}^{4} a_j T_j + E_w(\epsilon_{ed}(T_c^4 - T_4^4) + q_{ed} u_2) \qquad [2]$$

where T_k, $k = 1, \cdots, 4$ represent the normalized temperatures (normalized w.r.t. 300K). Furthermore equation [2] represents the boundary conditions on the wafer edge. E_w is the normalized emissivity (normalized w.r.t. 0.7), T_c represents the normalized (lumped) temperature of the chamber walls, and u is a vector of the normalized lamp powers. i.e. $u = [u_1 \ u_2 \ u_3]^T$, with $0 \leq u_j \leq 1$, $j = 1, 2, 3$. The model presented in (2) corresponds to $E_w = 1$, and $T_c = 1$, and the parameters are given in (2) to be,

$$B = \begin{bmatrix} -12.3111 & 15.7093 & -6.1059 & 2.7077 \\ 9.7005 & -34.5634 & 39.1722 & -14.3093 \\ -6.4371 & 66.2134 & -298.7683 & 239.0280 \end{bmatrix}$$

$$a = [-0.3777 \ 2.8255 \ -29.8354 \ 27.3875]; \quad q(r_k) = \begin{bmatrix} 7.58 & 6.60 & 5.82 \\ 1.51 & 2.62 & 5.16 \\ 8.38 & 8.61 & 8.64 \end{bmatrix} \qquad [3]$$

$$\kappa = 0.0021; \quad \epsilon = 0.0012; \quad \epsilon_{ed} = 0.0037; \quad q_{ed} = 2.011$$

The structure of the above model is similar to that employed by (6) for another RTP system. Furthermore, in (6), the authors carried out model identification experiments, and found that all the parameters of the model were consistent. except E_w, which varied depending on processing conditions.

For purposes of the controller design. we assume that E_w varies between 0.5714 (corresponding to an emissivity of 0.4), and 1.286 (corresponding to an emissivity of 0.9). Furthermore, we assume that the normalized temperature of the chamber T_c varies between 1 (room temperature), and 1.588 (200°C). The range of emissivity variation is based on results published in (7).

CONTROLLER DESIGN

Consider the closed-loop system given in figure 1. Here, w represents the noise entering the RTP. In our case, it represents the variation in the emissivity (E_w), and the wall temperature (T_c). $W_u(s)$ is a matrix of filters incorporated to shape the controller response, and the implemented controller consists of both $W_u(s)$, and C, the latter being the block that we synthesize. r and $W_r(s)$ are fictitious signal, and filter incorporated for design purposes alone, and are replaced by the reference trajectory when the controller is actually implemented. We bring the wafer temperature up to

$400^\circ C$ in open-loop mode, and then engage the controller. It is assumed that the lamp powers u_1, u_2, u_3 at this time are in vicinity of 0.5, 0.1, and 0.4 respectively. The reference trajectory is illustrated in figure 2.

To avoid fast transients in the lamp powers, $W_u(s)$ is chosen to be a low pass filter as $W_u(s) = \frac{0.5}{s+0.5}I_{3\times3}$, where $I_{3\times3}$ is a 3×3 identity matrix. To match the reference trajectory, we choose $W_r(s) = \frac{0.15}{s+0.15}$, or in its state space form as

$$\dot{\tilde{r}} = -0.15\tilde{r} + 0.15r \qquad [4]$$

with $r \in R$. Here, due to the asymmetric nature of the reference trajectory, we choose R as a function of $\tilde{r}$ as follows, $R = [\tilde{r}, 4.24]$ if $\tilde{r} < \bar{T}$, or equal to $[\bar{T}, 4.25]$ else. Here, $\bar{T} = 2.744$, and corresponds to $550^\circ C$, i.e. the ramp down temperature. We furthermore define $l(e)$ in figure 1 as

$$l(e) = l(\tilde{r}, T) = \max_{j=1,\dots,4} \frac{1}{2}(\tilde{r} - T_j)^2 \qquad [5]$$

Here, $\frac{1}{2}$ is just a scaling factor, and the cost simply reflects the maximum deviation of the temperatures from the fictitious reference ($\tilde{r}$).

We approximate the algebraic equation [2], as a fast time scale subsystem. Employing this approximation, we can write the RTP dynamics in the following functional form

$$\dot{T}(t) = f(T(t), u(t), w(t)) \qquad [6]$$

where $w(t) = [T_c(t)\ E_w(t)]^T$ represents the bounded noise corresponding to variations in the chamber temperature and the wafer emissivity. We now design the controller as follows. We first augment the RTP model with the state space realizations of the filters $W_u(s)$, $W_r(s)$ to obtain

$$\dot{\hat{X}} \triangleq \begin{bmatrix} \dot{T} \\ \dot{x} \\ \dot{\tilde{r}} \end{bmatrix} = \begin{bmatrix} f(T, x, w) \\ -0.5x + 0.5\bar{u} \\ -0.15\tilde{r} + 0.15r \end{bmatrix} \triangleq g(\hat{X}, \bar{u}, w, r) \qquad [7]$$

where $x \in \mathbf{R}^3$ is a vector of states corresponding to $W_u(s)$, and $\tilde{r} \in \mathbf{R}$ is the state corresponding to $W_r(s)$. Furthermore, $\bar{u} \in \mathbf{U}$, where the set $\mathbf{U}$ is defined by the constraints placed on the lamp powers (i.e. the individual lamp powers each lie in the interval $[0,1]$).

We now discretize the system via an Euler transform corresponding to a sampling time of 0.1 seconds, and taking the union of the right hand side over all possible values of w, and r, we obtain

$$\hat{X}[k+1] \in \mathcal{F}(\hat{X}[k], \bar{u}[k]) \qquad [8]$$

Since, we are going to engage the controller only after the wafer temperature reaches $400^\circ C$, and we have assumed that the lamp powers are in the vicinity of $[0.5\ 0.1\ 0.4]^T$, we fix the nominal initial conditions for this system as

$\hat{X}_0 = [2.244\ 2.244\ 2.244\ 2.244\ 0.5\ 0.1\ 0.4\ 2.244]^T$.

It can then be shown (8) that if there exists a solution V to the following stationary dynamic programming equation,

$$V(\hat{X}) = \inf_{u \in U} \sup_{p,q \in \mathcal{F}(\hat{X},u)} \{|l(p) - l(q)|^2 - \gamma^2 |p - q|^2 + V(p)\} \qquad [9]$$

with $V(\hat{X}) \geq 0$, $V(\hat{X}_0) = 0$, then the controller $\hat{u}(\hat{X})$ so obtained is such that

$$\gamma \geq \begin{cases} \max_{j=1,\ldots,4} |\hat{r}[k] - T_j[k]| \text{ for all } k, \text{ if } \hat{X}[0] = \hat{X}_0 \\ \limsup_{k\to\infty} \max_{j=1,\ldots,4} |\hat{r}[k] - T_j[k]| \text{ if } \hat{X}[0] \neq \hat{X}_0 \end{cases} \qquad [10]$$

Equation [9] is solved off-line by discretizing the state space and employing linear interpolation combined with iterative dynamic programming along the lines of Luus (9). The control values are stored in a table indexed by the states. When the controller is implemented, one simply carries out a table look-up coupled with linear interpolation to obtain the control values. We iteratively tests different values of $\gamma > 0$ such that a solution V exists to equation [9], and the smallest value of γ is found to be 0.1.

RESULTS

For purposes of the simulation, we let T_c, the chamber wall temperature be determined by a slow subsystem. The value of T_c varies between 90°C to 160°C, depending on the wafer emissivity. The wafer is heated in open-loop mode under constant lamp powers. These powers were fixed as $u_1 = 0.5$, $u_2 = 0.1$, and $u_3 = 0.4$. Once, T_1 reaches 400°C, the controller is switched on. Figure 2 shows the reference trajectory, and the four temperature trajectories generated by the closed-loop system with a wafer emissivity of 0.65. Figure 3 (top) shows a plot of the error incurred in the mean wafer temperature with respect to the reference for various cases. Figure 3 (bottom) illustrates the standard deviation of the four temperature measurements for various cases.

In all the cases, the mean wafer temperature is within 1°C of the desired steady state value. One can in fact, incorporate an integral control action during steady state, and drive this error to zero. Moreover, for all the cases, the temperature standard deviations are less that 0.7°C, and after an initial transient rapidly decrease to their steady state values. The oscillations observed in the error between reference and mean temperatures can be further reduced by using lower ramp rates.

CONCLUSION

A methodology to design robust multivariable nonlinear controllers for RTP systems was presented. The current controller is robust to emissivity variations, as well as to variations in the chamber wall temperature. Moreover, one could also incorporate additional sources of uncertainty, such as changes in the wafer conductivity. Excellent tracking and temperature uniformity are achieved for a wide range of operating conditions. Alternate cost functions $l(\hat{r}, T)$ need to be investigated to explore the possibility of further performance improvements. Also, linking the controller to a dynamic run to run controller proposed by (10) needs to be looked into.

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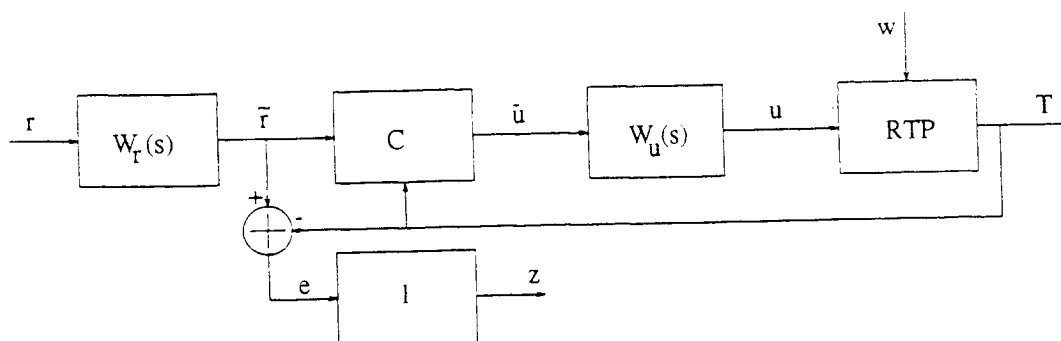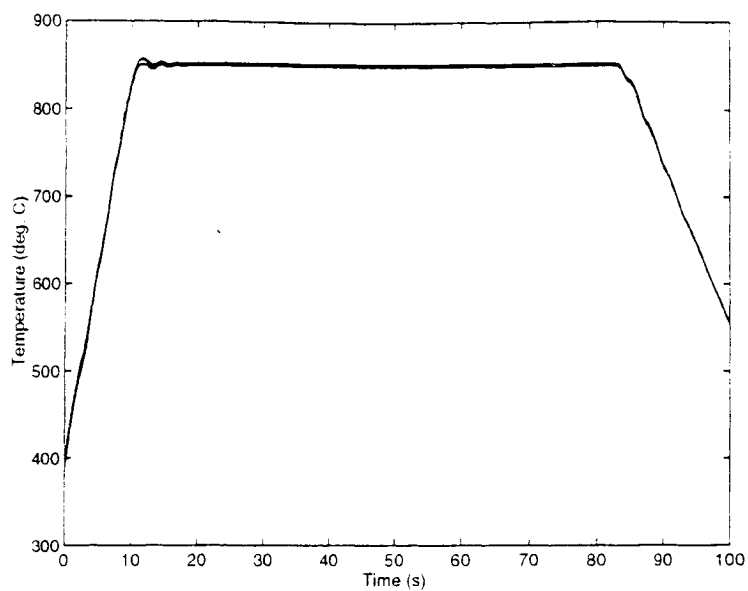
Fig. 1: The closed-loop system.

Fig. 2: Reference (dashed), closed-loop temperatures (solid) (wafer emissivity=0.65).
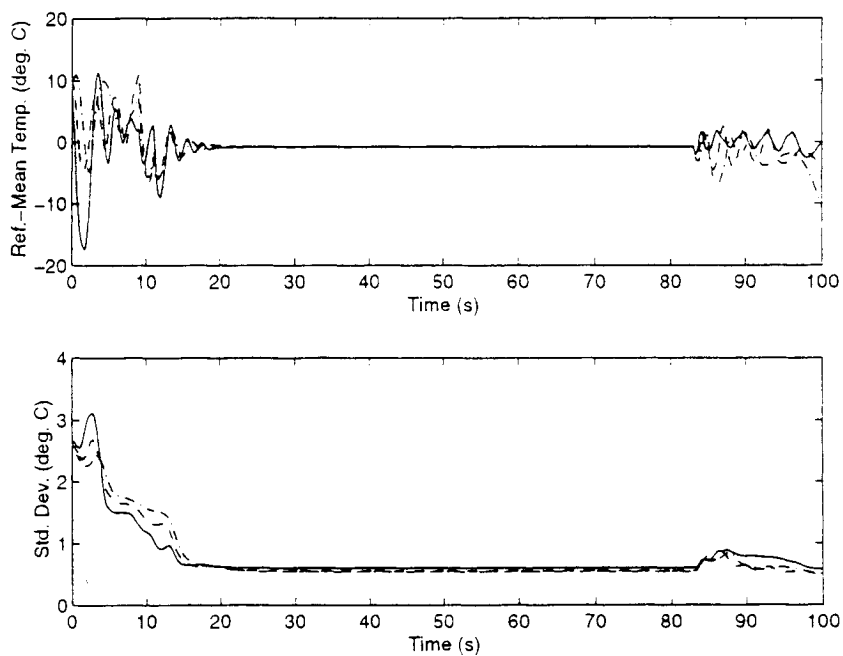

Fig. 3: Tracking error (top), temperature standard deviations (bottom) for various wafer emissivities: 0.4 (dash-dot), 0.65 (dashed), and 0.9 (solid).