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Nonlinear system identification of rapid thermal processing

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Abstract

Identification of rapid thermal processing parameters is examined to find a more accurate model to predict and control the temperature of semiconductor wafers during processing. In this paper, a Wiener model is applied to identify the significant dynamics of an RTP system. A recursive method is developed to simultaneously estimate the model parameters and states with respect to parameter variation in RTP systems under process noise. The identification result shows that the model's prediction error was greatly reduced as compared to a linear model. The proposed method can also be easily applied to model-based adaptive control.

Keywords: Identification; Nonlinear models; Kalman filters; Measurement noise; Recursive estimation; Adaptive control

1. Introduction

Rapid thermal processing (RTP) is a key technology for single-wafer fabrication operations in semiconductor manufacturing. The requirements imposed by the need for high quality, high yield, and increasing feature sizes, as well as the competitive nature of semiconductor manufacturing, motivates this interest in model identification of RTP systems for control. Over the last few years, many RTP system parameters have been identified through coarse models, but the shortcomings of these models severely limit process-control accuracy.

RTP systems heat the wafer using radiative energy generated by several lamps placed near the wafer. The most common concern in manufacturing is thermal uniformity across a wafer during processing. Since the desired heating and cooling rates are often very high, the resultant stresses can easily exceed the plastic limit of the wafer (Campbell, Knutson, Liu, & Leighton, 1991; Jin & Hyun, 2001). Experiments have shown that, given an accurate enough model, the nonuniform temperature of the wafer can be controlled by adjusting the relative power of individual lamps, which alters the heat flux density of a wafer in RTP (Cho & Gyuyi, 1997; Gyurcsik, Riley & Sorrell, 1991; Acharya et al., 2001). Most approaches to model identification in RTP systems use a linear approximation model such as the time constant and gain (TG) model (Cho, Paulraj & Kailath, 1994), the state-space model (Cho & Kailath, 1993), and a physics-based numerical calculation model (Campbell et al., 1991; Wang & Spanos, 2002). However, the nonlinearity and parameter variation during processing prevent us from obtaining a precise model with reliable identification for a wide range of wafer temperatures. Some recent techniques on model identification have been studied in order to identify an accurate model for the RTP system.

In this paper, we present some initial experimental results on the development of a nonlinear Wiener model (Schetzen, 1980) for RTP systems. The model is valid over a larger operating envelope than a linear time-invariant model. A recursive method based on the

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Extended Kalman Filter (Ljung, 1979) is applied to simultaneously estimate the model parameters and states under parameter variation in RTP systems and process noise. We also explore the implications for the future design of model-based adaptive control systems.

2. The identification problem of rapid thermal processing

A small custom RTP system, shown in Fig. 1, was used in identification. In this system, electrical energy as system input is supplied to one pot lamp arranged in the center and two ring cylindrical lamps arranged in the middle and edge of the heater, respectively. Energy transport is achieved both by radiation through a quartz window onto a thin wafer and by reflections off the walls. The low thermal mass of a single wafer allows the RTP system to rapidly increase wafer temperatures; the cold-wall system allows the wafer to be quickly cooled as well. Three thermocouples are mounted on the surface of the wafer to measure the temperature at its center, middle, and edge (the system output).

To capture the significant dynamics of this kind of physical system, we attempted to use a nonlinear Wiener model. The Wiener model is a kind of *block-oriented nonlinear model* consisting of a dynamic linear submodel and a static or memoryless nonlinear block, illustrated in Fig. 2. The advantages of using this kind of model lie in low computational cost for identification and suitability for control design. Here the model form is chosen as the state space representation of the linear submodel (**A B C D**) and a nonlinear function $\varphi(*)$ indicating static nonlinearity defined by

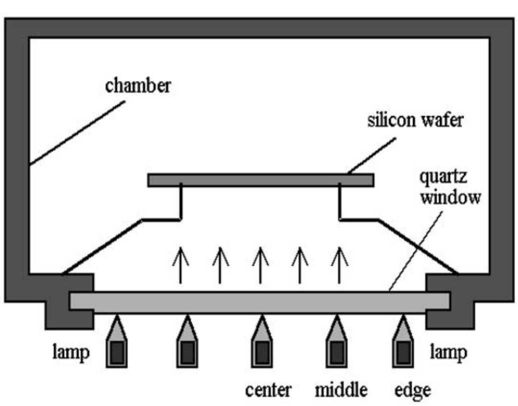

Fig. 1. Schematic of the small RTP system.

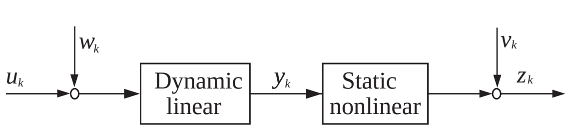

Fig. 2. Wiener model.

$$\begin{aligned}\mathbf{x}_{k+1} &= \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k + \mathbf{w}_k,\\ \mathbf{y}_k &= \mathbf{C}\mathbf{x}_k + \mathbf{D}\mathbf{u}_k,\\ \mathbf{z}_k &= \varphi(\mathbf{y}_k) + \mathbf{v}_k.\end{aligned} \tag{1}$$

It is assumed that (1) both **w** and **v** are zero-mean stationary stochastic processes with rational spectral density; (2) the nonlinear function $\varphi(*)$ is differentiable, and hence it can be approximated by a set of polynomials; (3) the physical parameters in RTP vary slowly during the processing and within a small range; and (4) the RTP system was treated as a three-input and three-output system in our experiment. Now the identification problem is: given the power consumption of each lamp (the model input $\mathbf{u}_k$) and the temperature of the wafer (measured output $\hat{\mathbf{z}}_k = [\hat{z}_{k,1}, \hat{z}_{k,2}, \hat{z}_{k,3}]$), determine a state space realization (**A B C D**) and a parametric estimation of the static nonlinearity. Since it is impossible to measure the internal signal $\mathbf{y}_k$, let $\hat{\mathbf{y}}_k = [\hat{y}_{k,1}, \hat{y}_{k,2}, \hat{y}_{k,3}]$ be the estimated output of linear submodel $\mathbf{y}_k$ in the sequel.

3. Extended Kalman filter-based recursive identification

3.1. Canonical parameterization of the Wiener model

In general, the linear dynamics and static nonlinearity of the Wiener model cannot be independently identified because of the models cascade structure (Billings & Fakhouri, 1982). We use a canonical parameterization of the two blocks. Since a scale factor can be arbitrarily distributed between the linear dynamics and the static nonlinearity without affecting the input–output characteristics of the model, the gain can be fixed in one of them. Let the Wiener model be parameterized in the pseudo-observability form (Ljung, 1997) of the linear submodel and the Chebyshev approximation of the static nonlinearity,

$$\begin{aligned}&\mathbf{A}(\theta_l) = diag[\mathbf{A}_1, \mathbf{A}_2, \mathbf{A}_3],\\ &\mathbf{B}(\theta_l) = [\mathbf{B}_1, \mathbf{B}_2, \mathbf{B}_3],\\ &\mathbf{C}(\theta_l) = diag[\mathbf{C}_1, \mathbf{C}_2, \mathbf{C}_3],\\ &\mathbf{D}(\theta_l) = \mathbf{0},\\ &\varphi_i(\hat{y}_{k,i}) = \gamma_{0,i}T_0 + \gamma_{1,i}T_1 + \cdots + \gamma_{p-1,i}T_{p-1},\\ &\quad i = 1, 2, 3,\end{aligned} \tag{2}$$

where $\mathbf{A}_i$, $\mathbf{B}_i$, $\mathbf{C}_i$ are defined as

$$\mathbf{A}_i = \begin{bmatrix} 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 1 \\ \times & \times & \times & \times & \times \end{bmatrix}, \quad \mathbf{B}_i = \begin{bmatrix} \times \\ \times \\ \vdots \\ \times \end{bmatrix},$$

$$\mathbf{C}_i = [1 \quad 0 \quad \cdots \quad 0], \quad i = 1, 2, 3$$