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Sliding mode control design for a rapid thermal processing system

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HIGHLIGHTS

- For a RTP system, dominant mode based sliding mode controller is proposed.
- Temperature accuracy and uniformity when heating are enhanced.
- The dynamics of the dominant mode is derived by Galerkin's method.
- Quasi-sliding mode control is proposed to eliminate the chattering effect.
- The temperature is estimated through a limited number of sensors.

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ABSTRACT

A sliding mode control strategy is developed for temperature control of a rapid thermal processing (RTP) system to enhance temperature accuracy and uniformity when heating in this work. Temperature dynamics of the RTP is nonlinear and infinite-dimensional while order of the controller should be finite due to implementation limitations. Developing a nonlinear low-order controller for the system is important if accurate and uniform control of the temperature is required. This work addresses this issue by developing a sliding mode controller based on the dominant modes of the system. The schemes are applied to a RTP system and excellent performances are achieved.

1. Introduction

Rapid thermal processing (RTP) technology with its limited thermal budget and its compatibility to flexible single-wafer processing is wildly used in semiconductor manufacturing. The problem hindering application of the RTP is that it is hard to obtain the temperature accuracy due to the nonlinearity of the RTP system. Moreover, there is an increasing requirement on the temperature uniformity as the semiconductor industry moves towards ultra large scale integration (ULSI) on wafer with bigger size (Roozeboom and Parekh, 1990). It was shown by Kakoschke and Bussmann (1989) that the temperature uniformity was limited by radiation loss at the wafer edge in stationary state and by non-uniform illumination of the wafer during ramp-up. Structures on the wafer are also potential sources for non-uniform heating. In the case of wafer with patterned over-layers on the front side, Vandenabeele et al. (1989) showed the temperature non-uniformity over the wafer experimentally and theoretically, on which the dependence of oxide thickness and pattern geometry was revealed.

Sophisticated control schemes have been developed and applied to RTP systems to achieve accuracy and uniformity of the temperature. A physically based macroscopic model of a RTP system developed from the first principles was linearized and then used in the scalar control design (Balakrishnan and Edgar, 2000). It was claimed that compared to empirically determined controllers, the proposed model-based controller was shown to perform favorably towards meeting very stringent specifications. But this control design only considered the temperature of a single point on the wafer, which was disadvantageous to the temperature uniformity. Instead of scalar control, multi-variable control whereby three rings were dynamically controlled to provide for control over the spatial flux profile was used and offered good temperature uniformity over transients, thus improving reliability of individual processes (Apte and Saraswat, 1992). In order to compensate some modeling errors between the model and the actual system, iterative learning control schemes proposed by Yang et al. (2003) and Choi and Do (2001) were applied to RTP systems without exact information on the dynamics.

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The above control approaches are based on some linear models of the nonlinear dynamical system. When the nonlinearities of the systems are significant, especially in high temperature, the performances of the linear model-based controllers are weak. Nonlinear models (Cho et al., 2008) should be constructed and considered in the design of controllers for RTP systems. Lin and Jan (2001) used a high-order nonlinear model describing the temperature dynamics of a RTP system for the feed-forward controller design. Jeng and Chen (2013) proposed a nonlinear control strategy based on modeling the RTP system as a nonlinear Wiener model. Neural fuzzy network was considered by Lai and Lin (1999) and Lin et al. (1999) for learning inverse control of RTP systems. With the great ability of compensating nonlinear functions, neural fuzzy network-based controllers showed effective performance of tracking a temperature trajectory.

Sliding mode control is another type of control method which is promising for dealing with the nonlinear uncertainty of system, showing superb performance which includes insensitivity to parameter variations, and complete rejection of disturbances. Large quantities of researches have been developed on the theory and application of the sliding mode control (Perruquetti and Barbot, 2002; Young et al., 1999). However, most of the sliding mode control strategies are designed for lumped parameter systems. In this paper, we will introduce the sliding mode control to the RTP process which is a distributed parameter system. The difficulty is that instead of finite-dimensional states controlled in lumped parameter system, infinite-dimensional state should be considered in distributed parameter system. In the RTP system, the temperature on the whole surface, which is an infinite-dimensional state variable, should be accounted for. The control approaches discussed above approximated the infinite-dimensional system dynamics with finite-dimensional models on a few discretization points. However, using these kinds of spatial discretization methods for control has some weaknesses. Firstly, in order to achieve an acceptable control precision, the number of the discretization points would be large. This will result in a large quantity of control inputs which is impossible to be implemented in the RTP system (Seborg, 1984). Secondarily, they lead to the effects of both observation and control spillover which could affect the performance of the control system severely (Meirovitch and Baruh, 1983). Furthermore, when the spatially distributed nature of the temperature is very strong, using the truncated model from the discretization methods may make the control quality undesirable.

An alternative way of constructing the reduced model for control we use in this work is based on dominant modes of the system. The system state can be divided into a dominant part and a remaining trivial part according to the eigenfunctions and the reduced models of the dominant modes can be obtained by Galerkin's method (Deng et al., 2005; Hoo and Zheng, 2001; Qi and Li, 2009). The proportion of the modes in the trivial part will decay rapidly and then the dominant modes would capture the principal dynamics of the state. A sliding mode control strategy is developed based on this nonlinear reduced model of the dominant modes. Due to the great capacity of sliding mode control for compensating nonlinear uncertainty, the control method shows superb performance for thermal regulation of the RTP system.

This paper is organized as follows. In Section 2, a brief description of the RTP setup used in this work and its mathematical model are given. Section 3 describes the method of model reduction and Section 4 discusses the issue of state estimation. We develop the sliding mode controller based on the reduced model and the state estimation in Section 5. Finally, in Section 6, we describe the application of our control strategies to the RTP system. Section 7 concludes the paper.

2. Model description

There are three types of heat transfer in the RTP chamber when heating: conduction, convection and radiation. The energy balance of the wafer gives:

$$\rho C \frac{\partial T}{\partial t} = q_k + q_c + q_r \tag{1}$$

where ρ is the wafer density, C is the specific heat, T is the wafer temperature pertaining to position and time, t is the time and q_k, q_c and q_r are the heat transfer rates by conduction, convection and radiation, respectively.

We use the same system configuration in this work as Dassau et al. (2006). The RTP system named as Steag CVD system has halogen lamps above, which are arranged in different zones as the heating system. The silicon wafer is placed on a rotating support to decrease the temperature distribution in different azimuths. The reaction chamber is closed from above by a quartz window, which allows for radiative heating of the wafer, while at the same time permits wafer processing under vacuum. Fig. 1 illustrates a schematic diagram of that RTP system. In addition, we only account for the temperature control during the heating and the process portions of a processing cycle in this work rather than the cooling stage. Thus, no cooling flow is needed and heat transfer by convection can be ignored.

Since the silicon wafer is very thin, we only consider the surface temperature on the wafer and a two-dimensional system model is sufficient for presenting the dynamics. Furthermore, since the wafer is positioned on the rotating plates, temperature variation in azimuth direction can be neglected and the system dynamics can be simplified into a one dimensional model with the radius as the following parabolic partial differential equation (PDE):

$$\frac{\partial T(x,t)}{\partial t} = \frac{k}{\rho C R^2}\frac{\partial}{\partial x}\left(\frac{\partial T(x,t)}{\partial x}\right) - \frac{F\varepsilon\sigma}{Z\rho C}\left(T^4(x,t) - T_a^4\right) + \frac{\varepsilon}{Z\rho C} q(x,t) \tag{2}$$

with the boundary conditions:

$$\frac{\partial T(x,t)}{\partial x} = 0 \quad \text{at } x = 0 \tag{3}$$

$$\frac{\partial T(x,t)}{\partial x} = 0 \quad \text{at } x = 1 \tag{4}$$

and initial condition:

$$T(x,t) = T_{ini}(x) \quad \text{when } t = 0 \tag{5}$$

where x is the normalized radius coordinate, k is the thermal conductivity, F is the reflective coefficient, ε is the emissivity of the wafer surface, σ is the Stephan–Boltzmann constant, Z is the wafer thickness, T_a is the temperature of the quartz window, q is the heat

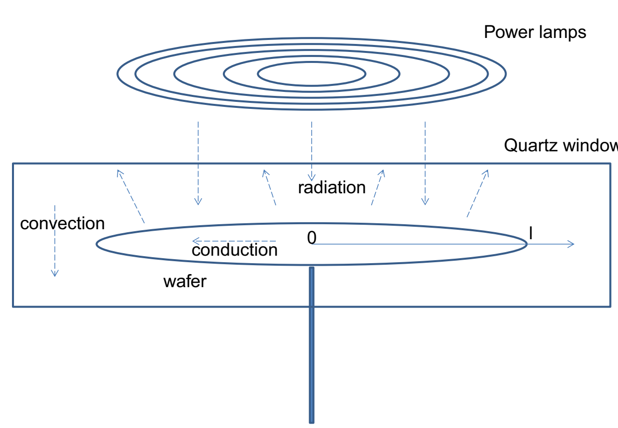

Fig. 1. The schematic of a RTP system.