Chemical Engineering Science 174 (2017) 146–156

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Combined iterative learning and delta-operator adaptive linear quadratic Gaussian control of a commercial rapid thermal processing system

Wangyun Won [a], Kyungtae Park [b,*], Jiyong Kim [c,*]

[a] Department of Chemical and Biological Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA
[b] Energy Plant Group, Korea Institute of Industrial Technology, Busan 46742, Republic of Korea
[c] Department of Energy and Chemical Engineering, Incheon National University, Incheon 22012, Republic of Korea

HIGHLIGHTS

- A novel control system for a commercial rapid thermal processing system.
- Modified delta operator LQG control in a Smith predictor configuration.
- Constrained ILC to satisfy input constraints and to improve temperature uniformity.
- Model parameter estimator to address model discrepancy from an actual system.
- Performance validation in a numerical RTP process.

ARTICLE INFO

Article history:
Received 4 September 2016
Received in revised form 10 May 2017
Accepted 8 August 2017
Available online 9 August 2017

Keywords:
Delta operator
Smith predictor
Iterative learning control
Linear quadratic Gaussian
Model adaptation
Semiconductor

ABSTRACT

Rapid thermal processing (RTP) units are used for various semiconductor fabrication steps mainly due to the short processing time, which results in a low thermal budget and improved product quality. In this study, we propose a comprehensive control system for the RTP unit by combining a linear quadratic Gaussian (LQG) controller, a constrained iterative learning controller (ILC), and a model parameter estimator. The control system is developed to resolve the issues caused by a short sampling time, which is required to meet the refractory control objectives of the modern RTP system (e.g., rapid ramping and a high degree of temperature uniformity). LQG control is selected because most required computations are conducted offline prior to each run and only minor computations are conducted in real time. The LQG control is constructed in a Smith predictor configuration so that a delayed model can be easily incorporated. The LQG control algorithm is modified from the standard formulation to include a quadratic penalty term for input deviation from the average value, to restrain the inputs from violating their constraints in real-time operation. The control algorithm and process model are developed in delta form so that the effect of the truncation error on the model accuracy can be alleviated at a high sampling rate. The constrained ILC updates the feedforward signal of the LQG controller in a batch-wise manner to further increase the temperature uniformity and to ensure that the inputs satisfy their constraints. To overcome model discrepancy from an actual system (patterned wafer), a small number of tunable parameters that can modify the major characteristics of the process model are incorporated into the identified state-space model (bare wafer) and are updated by a model parameter estimator. The performance of the proposed control system is validated in a numerical process, which is precisely constructed through identification experiments in a commercial 12-inch RTP unit.

1. Introduction

Rapid thermal processing (RTP) equipment is employed for various semiconductor fabrication steps, such as rapid thermal annealing and rapid thermal nitridation (Cho et al., 2005a). The most important advantage of the RTP unit over a conventional furnace processing unit is the short processing time, resulting in a low thermal budget and improved product quality (Oh et al., 2009). The demand for RTP units is expected to continuously increase. Recent expansion of the application of the RTP unit to flat panel displays, such as a liquid crystal and organic light emitting diode displays, is a good example (Kim et al., 2015).

---

* Corresponding authors.
E-mail addresses: pktcj@kitech.re.kr (K. Park), jykim77@incheon.ac.kr (J. Kim).

http://dx.doi.org/10.1016/j.ces.2017.08.010
0009-2509/

There are two important requirements for an RTP system: (1) a high degree of temperature uniformity over the wafer surface for combined time-varying and constant target temperature trajectories and (2) a short processing time, leading to rapid heating and subsequent fast cooling. Many research groups have presented various types of control methods, including decoupling control (Balakrishnan and Edgar, 2000), proportional-double-integral-derivative control (Huang et al., 2000; Lee et al., 2016), iterative learning control (ILC) (Cho, 2005; Cho et al., 2005a; Cho et al., 2005b; Lee et al., 2001; Yang et al., 2003), adaptive control (Choi et al., 2003), internal model control (Ebert et al., 2010; Schaper et al., 1999), linear quadratic Gaussian (LQG) control (Cho and Gyugyi, 1997; Won et al., 2009), and model predictive control (Dassau et al., 2006; Gwak and Masada, 2008; Jeng and Li, 2012; Jeng and Chen, 2013; Takagi and Liu, 2011), over the past two decades. However, as the wafer size increases and the surface patterns become finer and more complicated, the need for a new control technique that can meet the more refractory objectives of modern RTP systems, i.e., more stringent temperature uniformity and rapider ramping, arises.

A short sampling time is considered to be required to meet the performance requirements described above; it enables us to respond immediately to changes in disturbance and set points along the reference trajectory. However, reduction of the sampling time adds challenges to the task of control system development, as follows: (1) the discrete-time model becomes vulnerable to truncation error due to finite-bit data representation, which considerably reduces the accuracy of the process model (Goodwin et al., 2008; Middleton and Goodwin, 1990; Won and Lee, 2017), and (2) the control algorithm suffers from computational burden as the sampling rate increases (Won et al., 2010). Particularly, regarding the second issue, the online computational load should be sufficiently small so that the control computations can be completed within the given sampling interval (Seo et al., 2007). In the RTP system, solving quadratic programming (QP) online may not be allowed because it could drastically increase the computations. Breedijk et al. (1994) and Dassau et al. (2006) applied constrained model-based control that solves the QP problem at every sampling period, but their sampling interval was of the order of seconds and the model order was very small. In addition, the increase in model order with increasing number of delay steps at a high sampling frequency should be addressed to further reduce the computational burden.

Another challenge in the RTP system is model discrepancy from an actual system. The linear model for the controller design is usually derived from a bare wafer, while the control system is implemented to a patterned wafer, which has characteristics, such as thermal conductivity, that are totally different from the bare wafer. This is because of the high cost of the patterned wafer. This issue is very important from a practical point of view but has not been addressed elsewhere.

Accordingly, in this paper, considering the unique traits and operational requirements of an RTP system, we develop a comprehensive control system for the RTP unit by combining LQG control, a constrained ILC, and a model parameter estimator. First, the structure of LQG control follows the standard form, but the details contain elaborations and improvements: (1) the algorithm is developed in delta form so that the effect of the truncation error on model accuracy can be alleviated at a high sampling rate, (2) the objective is modified to include a quadratic penalty term for input deviation from the average value, to restrain the inputs from violating the constraints in real-time operation; and (3) the controller is designed to have dead-time compensation, i.e., Smith predictor, to reduce the computational burden and to embed the controller programming in a limited memory space of a commercial RTP equipment. Second, the constrained ILC is designed to update the feedforward signal of the LQG controller in a batch-wise manner, to further enhance the temperature uniformity using the extra degrees of freedom (DOF) available in the system and to ensure the inputs of the LQG controller are bounded within their constraints. Finally, to cope with the model error from an actual system with patterned wafer, a small number of tunable parameters that can modify the major characteristics of the process model are incorporated into the state-space model and are updated by the model parameter estimator.

The performance of the proposed control system is validated through the application to a numerical RTP system, which is precisely constructed via identification experiments in a commercial 12-inch RTP unit. It serves as not only a process model for controller design but also as a virtual process to investigate the proposed control system that could be seamlessly transferred to the actual RTP system. Therefore, all the major characteristics of the real RTP system, such as the process gain and dynamics, are accurately reflected in the simulated RTP system. The numerical study showed that the absolute temperature control error can be reduced by up to 0.3 °C, which is suitable for a commercial RTP system, with the aid of the proposed control system.

2. Process description

In this study, we consider the Korona$^{\mathrm{TM}}$1200*Plus* system from AP Systems Co. in Korea. The system has two identical RTP chambers for 12-inch wafers rotating at a maximum of 150 rpm. The inner surface of the chamber wall is gold-plated for maximum reflectivity, and the wall temperature is regulated by cool water circulating inside the wall. The unit has 220 bulb-type 0.7 kW-max tungsten-halogen (TH) lamps that are arranged in ten concentric circles for wafer heating and seven pyrometers for temperature measurement of the rotating wafer. The power of each lamp circle can be manipulated individually. Accordingly, the RTP system is a multivariable process that has ten inputs and seven outputs.

Fig. 1 illustrates the arrangement of the TH lamp array and the location of the temperature sensors. During wafer heating,

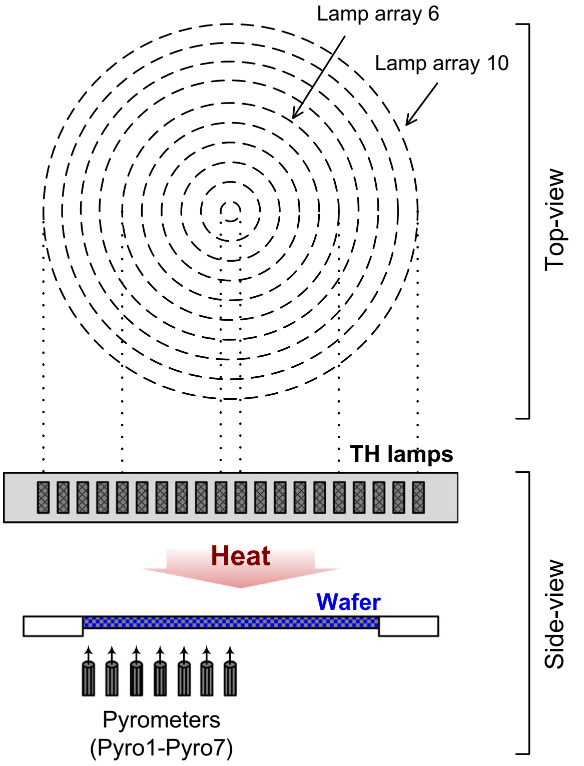

Fig. 1. Tungsten-halogen lamp array and temperature sensor locations.