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# Control strategies for thermal budget and temperature uniformity in spike rapid thermal processing systems

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ABSTRACT

Single wafer rapid thermal processing (RTP) is widely used in semiconductor manufacturing. A precisely applied thermal budget during RTP is crucial and relies on the temperature control of the wafer. However, temperature control in the RTP system with a spike-shaped temperature profile is a challenging task, and achieving perfect servo control is almost impossible because of the high temperature ramp-up/down rate and substantial nonlinearity of the process. This paper presents a novel method of control system design to provide a precise thermal budget in the spike RTP system. By tuning controller parameters and designing the set-point profile, the method targets thermal budget indices instead of temperature servo control. A nonlinear control strategy is proposed based on modeling the RTP system as a nonlinear Wiener model. Furthermore, a multivariable control structure is considered to maintain the temperature uniformity within the wafer. The simulation results show the effectiveness of the proposed control strategy and provide helpful guidelines for the design of a multivariable control configuration to achieve superior wafer temperature uniformity.



## 1. Introduction

Single wafer rapid thermal processing (RTP) is a crucial technology in the fabrication of semiconductor devices because it enables faster wafer processing with precise control of the thermal budget. The thermal budget is a critical process issue derived from the duration and maximum of wafer temperature beyond a specific reference value, as shown in Fig. 1. This index requires a tight process control in several processes, such as rapid thermal annealing, oxidation, nitration, and chemical vapor deposition in semiconductor manufacturing (Cho, Edgar, & Lee, 2008; Roozeboom, 1992). For example, the annealing process provides sufficient active energy for dopants to repair the lattice damage from ion implantation. This energy dominates the depth of junctions, and consequently affects the electric properties of devices, such as sheet resistance and junction leakages. Another crucial specification for RTP is the wafer temperature uniformity. A significant temperature difference in the wafer results in material failure caused by an increase of thermal stresses or considerable warpage (Chao, Hung, & Yu, 2003). A review of RTP control was conducted by Edgar et al. (2000).

The traditional RTP uses a soak-shaped temperature profile, as shown in Fig. 2(a). It consists of three steps: (1) rapid heating to the desired temperature, (2) processing for a prescribed time at constant temperature, and (3) rapid cooling to an ambient condition. However, because the dimension (line width) keeps shrinking, the fabrication of ultra shallow junctions requires small and precisely applied thermal energy. Therefore, the spike RTP system, as shown in Fig. 2(b), can be used to maintain the scaling requirements. In the spike RTP, the second step in traditional RTP is removed and the ramp-up/down rate of temperature trajectory increases (e.g., 200 °C/s for ramp-up rate) to prevent considerable spreading of the dopant profile (Jung, Gunawan, Braatz, & Seebauer, 2003). Gunawan, Jung, Seebauer, and Braatz (2004) designed a temperature program to produce the desired junction depth and maintain low sheet resistance. The spike-shaped temperature control dominates the reliability and yield of semiconductor manufacturing.

As shown in Fig. 1, the criteria of temperature trajectory for thermal budget control usually contain three indices: the duration of exceeding the reference value, the maximal temperature, and the ramp-up/down rate. Consequently, a triangular-shaped set-point profile is usually applied for thermal budget control. The conventional design for thermal budget control is implemented indirectly through servo control of the wafer temperature. In other words, the thermal budget is properly applied when the wafer temperature can closely follow its set-point. However, it is difficult to efficiently track a spike temperature set-point with high ramp-up/down rates in simple proportional–integral-derivative (PID) control systems (Jeng & Lee, 2012). Various control methods with varying complexity have been proposed for RTP to follow the desired temperature

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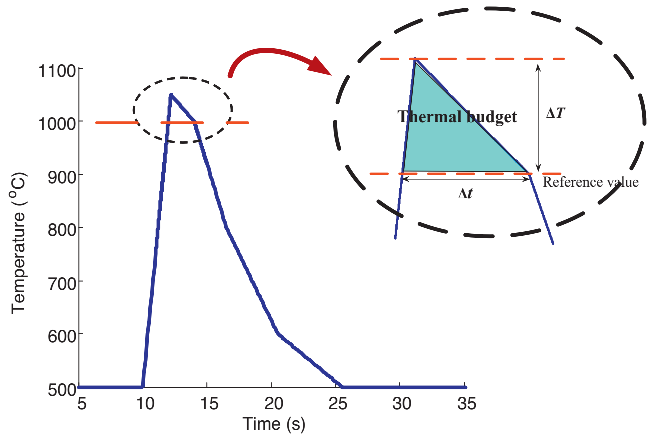


**Fig. 1.** Temperature profile and thermal budget in the spike RTP system.

trajectory and/or maintain the wafer temperature uniformity. They include model-based control (Balakrishnan & Edgar, 2000; Cho & Edgar, 2008), iterative learning control (Cho, Lee, Joo, & Lee, 2005; Choi & Do, 2001), adaptive control (Choi, Do, & Choi, 2003), internal model control (Schaper, Kailath, & Lee, 1999), and nonlinear model predictive control (Dasssu, Grosman, & Lewin, 2006). Huang, Yu, and Shen (2000) used a proportional–double integral-derivative ($PI^2D$) controller to eliminate offset error during the heating step. Most studies focused on the soak RTP system, whereas only few studies have discussed the control of the spike RTP system (Emami-Naeini et al., 2003; Su et al., 2007).

Achieving the desired thermal budget by designing a tightened servo control system is difficult and complex because of the high set-point ramp-up/down rate; therefore, our previous work (Jeng & Lee, 2012) considered targeting the control performance on the indices for thermal budget, instead of set-point tracking, by designing both the set-point profile and the controller. In this manner, the thermal budget can be precisely controlled and the controller design is much simpler. However, the previous work used a simple first-order linear model to represent the RTP system and considered only the single-input single-output (SISO) case. The RTP system exhibits highly nonlinear dynamics because of the effects of thermal radiation; therefore, it is more accurately modeled as a nonlinear model. To solve this problem, this study used a nonlinear Wiener model to represent the RTP system. The Wiener model is identified using a simple non-iterative algorithm. Therefore, a nonlinear control strategy is proposed based on extensions of the previous design method to manage the thermal budget control in spike RTP systems. Additionally, the temperature uniformity within the wafer during the heating/cooling process is also a crucial specification. The RTP equipment has several heating lamps, which are usually clustered into several adjusting zones for wafer temperature control. This study used the multivariable control structure to maintain superior temperature uniformity within the wafer. Moreover, two issues regarding the design of multivariable control configuration were discussed and their effects on temperature uniformity were investigated. One issue is the allocation of clustered lamps, and the other issue is the location of temperature measurements for control.

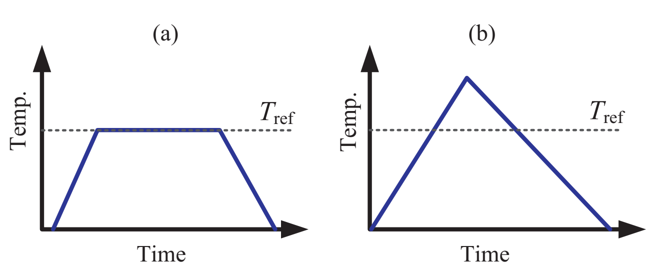


**Fig. 2.** Temperature profile in RTP systems: (a) soak and (b) spike.

The remainder of this paper is organized as follows. Section 2 introduces the RTP system and its physical model; Section 3 presents the problem of thermal budget control and a brief review of the linear model-based control design to achieve the desired thermal budget; Section 4 presents the proposed nonlinear multivariable control strategy for thermal budget and temperature uniformity in the spike RTP system; Section 5 provides the simulation results; and lastly, Section 6 offers a conclusion.

## 2. The RTP system

A schematic diagram of the RTP system is shown in Fig. 3. In an RTP chamber, power is supplied to several rings of tungsten-halogen lamps, and energy is transferred through a quartz window onto a thin semiconductor wafer through direct or reflective paths. The wafer temperature is controlled by manipulating the lamp power sources.

Physical models for the dynamics of wafer temperature of various complexities have been reported (Dasssu et al., 2006; Huang et al., 2000; Lee, Lee, Chin, Choi, & Lee, 2001; Schaper, Moslehi, Sarawat, & Kailath, 1994). This study used a lumped model, such as that by Huang et al. (2000) which was validated experimentally in several studies. Only temperatures in the radius ($r$) direction are of interest by assuming axisymmetric temperature distribution; therefore, the distribution in the axial ($z$) direction can be ignored.

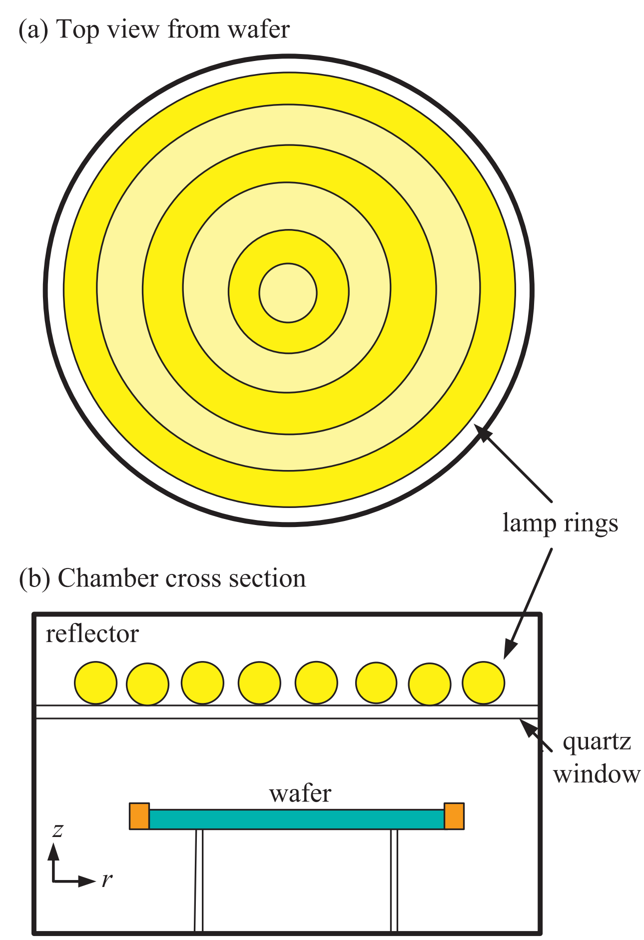


**Fig. 3.** Schematic diagram of an RTP equipment: (a) top view and (b) cross section.