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A Robust Controller Design for Rapid Thermal Processing in Semiconductor Manufacturing

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Abstracts The problem of temperature control for rapid thermal processing (RTP) in semiconductor manufacturing is discussed in this paper. Among sub-micron technologies for VLSI devices, reducing the junction depth of doped region is of great importance. This paper investigates existing methods for manufacturing wafers, focusing on the RTP which is considered to be good for formation of shallow junctions and performs the wafer fabrication operation in a single chamber of annealing, oxidation, chemical vapor deposition, etc., within a few minutes. In RTP for semiconductor manufacturing, accurate and uniform control of the wafer temperature is essential. In this paper, a robust controller is designed using a recently developed optimization technique. The controller designed is then tested via computer simulation and compared with the other results.

Keywords Rapid thermal processing, Semiconductor manufacturing, Robust control, H_∞ 2 degree-of-freedom model-following design.

1. Introduction

In VLSI devices several million transistors must be integrated in one chip area, and it is advantageous that the feature size of each transistor is reduced[3]. Among sub-micron technologies for VLSI devices, reducing the junction depth of doped region is of great importance. This paper investigates existing methods for manufacturing wafers, focusing on the RTP which is considered to be good for formation of shallow junctions and performs the wafer fabrication operation in a single chamber of annealing, oxidation, chemical vapor deposition, etc., within a few minutes.

In RTP for semiconductor manufacturing, accurate and uniform control of the wafer temperature is essential. Of the various techniques for RTP temperature control, model-based control such as LQG/LTR has shown the great potential for attaining good performance up to now(LQG/LTR controller development for RTP system[1], Optimization for finite-time tracking with actuator saturation[2]).

In this paper, a robust controller is designed using a recently developed optimization technique. More specifically, an H_∞ two degree-of-freedom(2-DOF) model-following controller design methodology developed by [7] is used. The controller designed is then tested via computer simulation and compared with the other results. The results obtained in this paper look promising in that the H_∞ controller works well on the RTP system.

2. Rapid Thermal Processing in Semiconductor Manufacturing

A variety of different steps are involved in semiconductor microelectronics manufacturing. These steps include oxidation, lithography, epitaxial film growth, annealing, chemical vapor deposition, etc. Each of these steps is a distinct part of the process and uses associated processing equipment. An important state-of-the art technique to perform some of these steps on RTP of which this technique has major advantages of semiconductor wafers. In the conventional electrical furnace-based techniques, the processing step involves several hours and the speed is limited by the large thermal masses of the walls. In contrast, in RTP only the wafer mass is heated or cooled and the RTP walls are water cooled and kept at room temperature. RTP is a versatile approach suitable for several different processing functions. These include rapid thermal annealing, rapid thermal cleaning, rapid thermal chemical vapor deposition, and rapid thermal nitridation. RTP systems are capable of increasing wafer temperature in excesses of $200°C/s$. This makes RTP an attractive alternative as thermal budgets are reduced.

From a manufacturing point of view, RTP fits naturally into the current cluster-tool concepts which promise IC fabrication lines which are more flexible, and much less capital intensive as compared to present billion dollar state-of-the-art fabs.

RTP is an essential technology for single-wafer processing. An advantage of single-wafer systems is the potential for better wafer-to-wafer uniformity. With a single-wafer system performing a given processing steps, each wafer is exposed to a processing environment which is nearly identical to the previous one, with the exception of any changes due to drift in equipment parameters. This is in contrast to the typical batch process in which great care must be taken to ensure uniformity across the entire wafer load since each wafer sees a slightly different process environment. In a single-wafer system, uniformity concerns are largely confined to maintaining good uniformity across the single wafer being processed. In addition to the potential for improved wafer-to-wafer uniformity, there are other advantages offered by single-wafer processing. In high-temperature processing steps, the large thermal mass associated with a batch of wafers typically results in relatively long times for temperature ramp up and cool down. The thermal budget maybe greater for a batch process than for a corresponding single-wafer process. Therefore, the single-wafer process has an inherent advantage[3].

A diagram of a typical RTP system is shown in Fig 1, taken from[5].

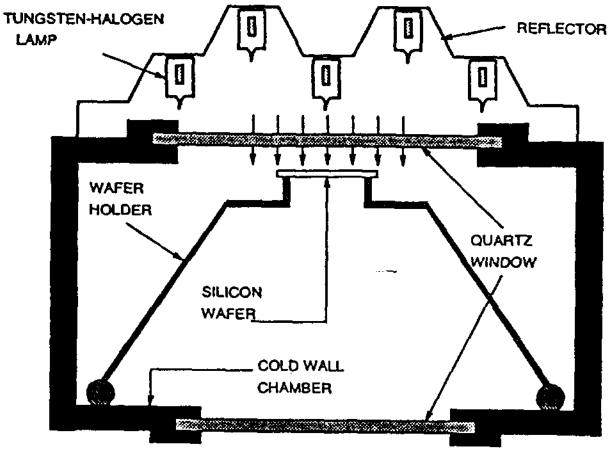

Fig 1. Schematic of the RTP system

With RTP a single wafer is heated quickly at atmospheric or low pressure under isothermal conditions. The processing chamber is made of quartz, silicon carbide, stainless steel, or aluminium with quartz window. The wafer holder is often made of quartz and contacts the wafer at a minimum number of places. A temperature measurement system is placed in a control loop to set wafer temperature. The RTP system is interfaced with a gas handling system and a computer that controls system operation. The wafer is heated by radiation via a lamp array.

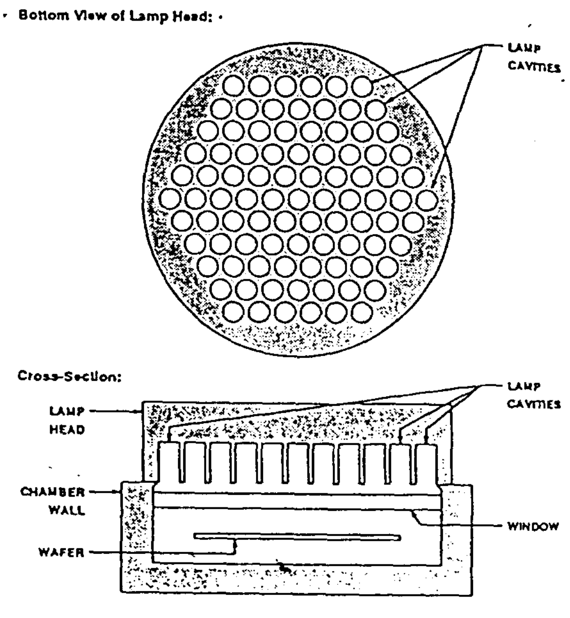

Fig 2. One-sided heating with hexagonal array of tungsten-halogen lamps

In one design (Fig 2), rings of tungsten-halogen lamps arrays are used as heaters (actuators) and are separated from the chamber by a quartz window. The lamp array has a hexagonal packing. The wafer is heated only from the top-side. There are several other competing alternatives for the lamp design. However, precise temperature control is required regardless of the lamp design. The chamber has a large number of inputs and outputs. It uses advanced pyrometers as temperature sensors.

3. A Robust Controller Design

3.1 RTP system modeling

The model incorporates radiative, conductive and convective heat transfer mechanisms and allows for chamber heat-up as observed in real RTP systems. However, for controller development it is desirable to use the simplest possible model structure capable to matching the phenomena observed in the RTP system in order to reduce the complexity of the developed controller.

A SISO model of an RTP system used for designing a model-based robust controller in this work is adopted from [2] and represented by the first order plant

$$P(z) = \frac{2.3164}{z-0.9964}$$

3.2 Controller Specifications

The RTP system is to follow a pre-defined temperature profile which is required along with minimal overshoots at transition and minimal spartial temperature variations during all phases of the profile. Temperature uniformity is required on all the wafer in spite of the fact that temperature is being measured only at a finite number of points. Precise temperature control is critical to this promising technology[2].

The requirements for the control design included:

1. a uniform temperature profile throughout the process recipe with less than a $\pm 2.5^{\circ}C$ temperature error band during ramps,

2. steady state temperature error less than $1.5^{\circ}C$ peak and less than $0.5^{\circ}C$ average, and

3. less than $5^{\circ}C$ overshoot(preferably none) at the end of the ramp with as fast a settling time as possible.

These requirements apply to bare silicon wafers and 'typical' process recipes such as temperature profile for oxide growth process.

3.3 An H_∞ 2-DOF Model Following Design

The problem of robust stabilization of normalized coprime factor plant descriptions as introduced in [4] has a certain benefit in that the optimal controller is synthesized by the solution of just two algebraic Riccati equations, unlike most H_∞ problems which require an iterative search on the H_∞-norm of a closed-loop transfer function to find the optimum. In practice, to design control systems using normalized coprime factorizations, the plant needs to be weighted to meet closed-loop performance requirements. A design procedure has been developed [8], known as Loop Shaping Design Procedure (LSDP), to choose the weights by studying the open-loop singular values of the plant, and augmenting the plant with weights so that the weighted plant has an open-loop shape which will give good closed-loop performance. The LSDP results in a one degree-of freedom control scheme.

Improved performance for tracking systems may be obtained by including a pre-compensator on the reference input. An analytical method based on model-following combined with the normalized coprime factor approach has been proposed in [7].

Fig 3 shows design configuration of the H_∞ 2-DOF model following approach.

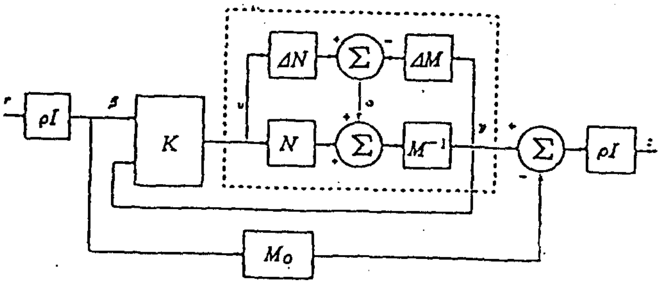

Fig 3. H_∞ 2-DOF model following design configuration

3.4 Controller Design Procedure

The object of the control design is to satisfy the control specifications and to ensure an adequate robust stability margin.

A procedure for designing an H_∞ 2-DOF controller of the RTP system is described below:

1. It is necessary to reshape the plant frequency response in order to meet the closed loop performance requirements. The loop shaping is done by premultiplying the plant by a loop shaping precompensator W. The loop shaping weighting function we decided on was

$$W = \frac{200(s+0.55)}{s(11s+1)}$$

in which the gain, and pole and zeros locations were arrived at by considering the required loop shape at high and low frequency. Integral action is used to boost low frequency gain. The zero at -0.55 is used to reduce the roll-off at cross-over, while the pole at -0.0909 ensures a low controller bandwidth. The corresponding shaped and unshaped open loop singular values plots are given in Fig 4.

2. Select a simple step response model for the closed loop system; See M_o in Fig 3. Our time response reference model was selected to be

$$M_o = \frac{120}{s+120}$$

This reference model has a rising time of 0.05 sec which is equal to 1 sampling time of 20mS in discrete case.

3. Find the minimal value γ_o in the robust stabilization problem. Lowest achievable value of γ is acquired by solving the Riccati equation. In this RTP model, we acquired $\gamma_o = 1.414$ for the robustness problem associated with GW.

The design was completed by setting $\rho = 1.77$ and this leads to $\gamma = 4.9521$ for the lowest achievable value.

3.5 Simulation Results

Simulation on RTP system is done according to the controller design procedure. Open loop unit step response is shown in Fig 5. Fig 6 shows unit step response of the closed-loop system composed by the H_∞ 2-DOF controller designed above. Rising time of the closed loop system is 0.05sec(ie, 1 sampling time). Reference following is satisfactory. Fig 7 shows response for temperature profile of oxide growth process. We can't see any differences between reference profile and output in Fig 7, but actually there is a $0.06°C$ temperature error band during ramps. However, it is very small error band compared with controller specification($\pm 2.5°C$ error band during ramps). Fig 8 shows PID controller and H_∞ 2-DOF control for RTP system. Though both have neither overshoots nor steady state temperature errors, the H_∞ 2-DOF control is superier to the PID control in a sense of rising time(PID : 0.35sec, H_∞ : 0.05sec).

4. Conclusions

In this paper, we applied the H_∞ 2-DOF model following design procedure to a SISO RTP system. Our design shows that the H_∞ 2-DOF controller performs well on the RTP system. Reference following for temperature profile of oxide growth process is good enough compared with controller specifications.

Further research for designing controller for MIMO model of the RTP system will be continued.

5. Acknowledgements

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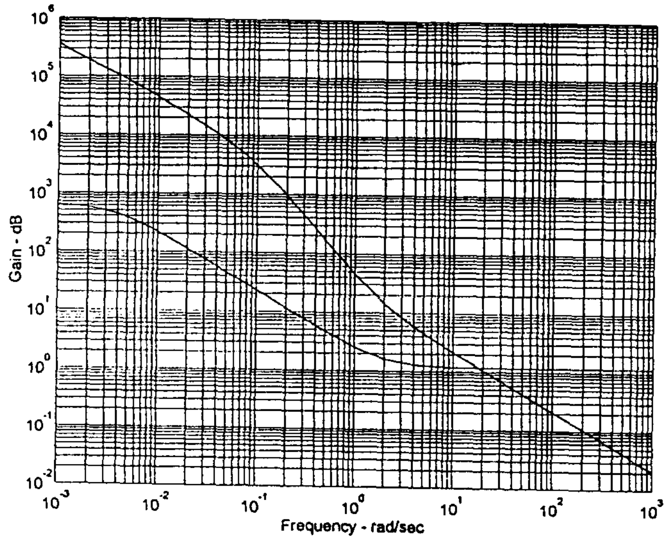

Fig 4. The shaped and unshaped open loop singular values

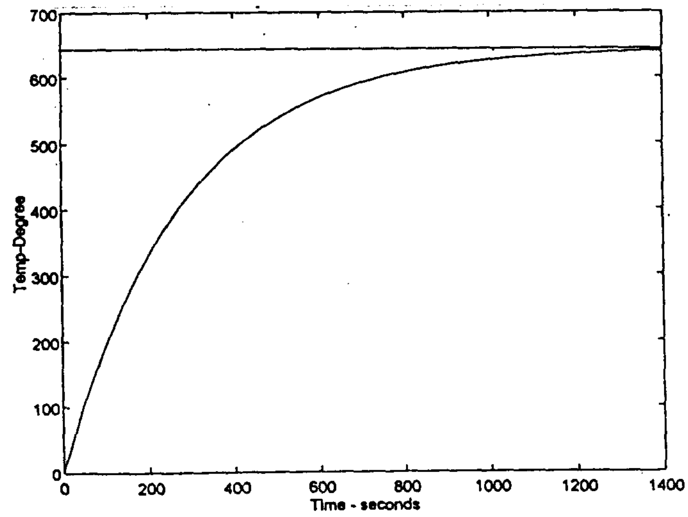

Fig 5. Open loop unit step response

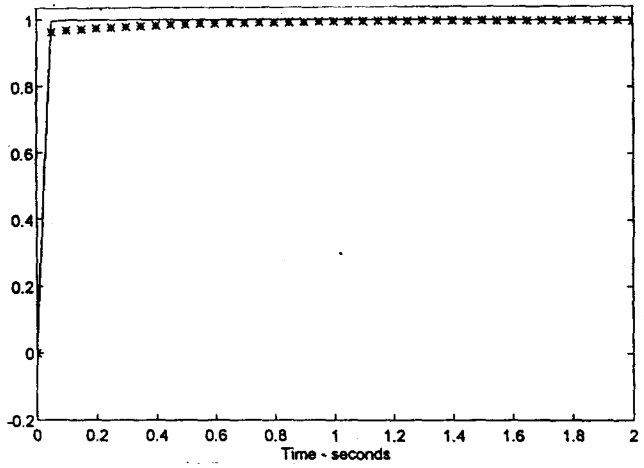

Fig 6. Closed-loop unit step response using H_∞ 2-DOF

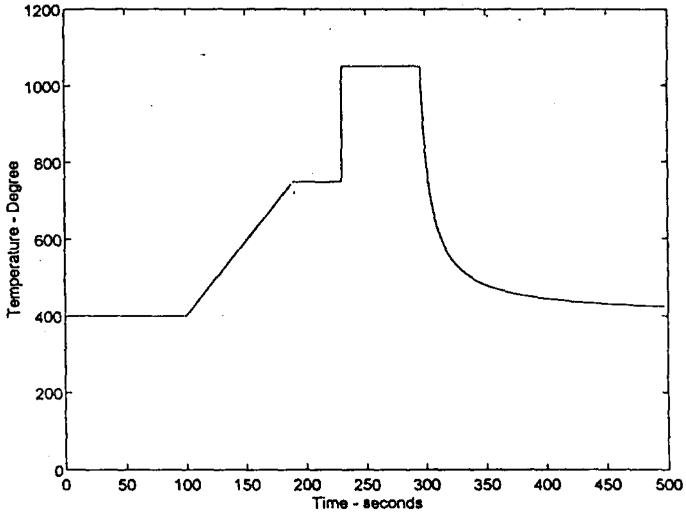

Fig 7. Closed-loop response on temperature profile

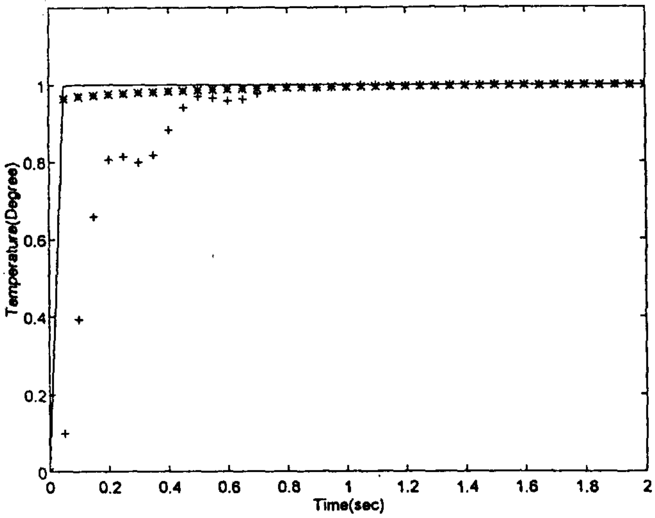

Fig 8. PID control(+) vs H_∞ 2-DOF control(*)