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PROCESSING OF SEMICONDUCTOR QUARTZ PHOTOMARKS ON BAKE-PLATES [1]

Weng Khuen HO, **Arthur TAY** and **Khiang Wee LIM**

Department of Electrical and Computer Engineering,
National University of Singapore,
10 Kent Ridge Crescent, S(119260)

Abstract: A feedforward control scheme is designed for robust performance of conductive heating systems used for lithography in microelectronics processing. It minimizes the loading effects induced by the common processing condition of placement of a quartz photomask at ambient temperature on a large thermal-mass bake plate at processing temperature. The feedforward control strategy is a model-based method using linear programming to minimize the worst-case deviation from a nominal temperature set-point during the load disturbance condition. This results in a predictive controller that performs a pre-determined heating sequence prior to the arrival of the substrate as part of the resulting feedforward/feedback strategy to eliminate the load disturbance. This procedure is based on an empirical model generated from data obtained during closed-loop operation. It is easy to design and implement for conventional thermal processing equipment. Experimental results are performed for a commercial bake plate and depict an order-of-magnitude improvement in the settling time and the integral-square temperature error between the optimal predictive controller and a feedback controller for a typical load disturbance.

Keywords: Feedforward Control, Thermal Processing, Constraints, Semicoductor Manufacturing

1. INTRODUCTION

Lithography is the key enabler and bottleneck controlling the device scaling, circuit performance and magnitude of integration for microelectronics manufacturing. This integration drives the size, weight, cost, reliability and capability of electronic devices. The lithography process accounts for $30 - 35\%$ of the costs of manufacturing integrated circuits (Plummer *et al.,* 2000). The most important variable to control in the lithography sequence is the minimum feature size or critical dimension (CD) which perhaps is the single variable with the most impact on device speed and performance (Edgar *et al.*, 2000). Figure 1 shows typical steps in a microlithography sequence. This includes numerous baking steps such as the prime bake, soft bake, post-exposure bake, and post-develop bake (Sheats and Smith, 1998). In some cases, additional bake steps are employed. Each of these bake steps serve different roles in transferring the latent image into the substrate (Sheats and Smith, 1998). Of these, the most important or temperature sensitive is the post-exposure bake step (PEB). The post-exposure bake step is critical to current Deep Ultra-Violet (DUV) lithography. It is used to promote chemical modifications of the exposed portions of the photoresists. For

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such chemically-amplified photoresists, the temperature of the substrate (wafer or reticle) during this thermal step has to be controlled to a high degree of precision for CD control (Parker and Renken, 1997).

Sturtevant et. al. (Sturtevant *et al.*, 1993) reported a 9% variation in critical dimensions per $1°C$ variation in temperature for a DUV photoresist. APEX-E resist has been shown to display a sensitivity close to $12\ nm/°C$, and UVIIHS 4 to $10\ nm/°C$ (Petersen, 1997). A number of recent investigation also shows the importance of proper bake plate operation on CD control (Crisalle *et al.*, 1988; Mohondro and Gaboury, 1993). According to the International Technology Roadmap for Semiconductors (ITRS) (Sem, 2000), the PEB resist sensitivity to temperature will be more stringent for each new lithography generation as depicted in Table 1. By the year 2010, the PEB resist sensitivity is expected to be only $1\ nm/°C$; making temperature control even more critical. To meet future temperature requirements for advanced lithography processes, it is important to reduce temperature variation of the baking process, which is the subject of this paper. The application of advanced computational and control methodologies has increased in recent years to improve yields, throughput, and, in some cases, to enable the actual process to print smaller devices (Edgar *et al.*, 2000; Limanond *et al.*, 1998; Schaper *et al.*, 1999*a*). The value of applying such mathematical systems science tools to microelectronics manufacturing has already been demonstrated in the area of photoresist thermal processing (Schaper *et al.*, 1999*a*; Schaper *et al.*, 1999*b*; El-Awady *et al.*, 1999; Ho *et al.*, 2000; Tay *et al.*, 2000; Lee *et al.*, n.d.; Palmer *et al.*, 1996), rapid thermal processing (Cho and Kailath, 1993; Stuber *et al.*, 1998; Schaper *et al.*, 1999*c*) and plasma processing (Vincent *et al.*, 1997; Hankinson *et al.*, 1997).

Thermal processing (Baking) is performed by placement of the substrate on a bake plate for a given period of time. This process is automated in the wafer fab, the next wafer arrives immediately after the baking of the first wafer. The current practice is to have the heated bake plate held at a constant temperature by a feedback controller that adjusts the heater power in response to a temperature sensor embedded in the plate near the surface. When the cold substrate is placed on the bake plate, the temperature of the bake plate drops before the heater controller gradually rejects this load disturbance. As the feedback controllers generally do not respond the same, plate-to-plate non-repeatability will also occur. Another case may be the implementation of a multi-zones controller where the zones do not respond to the load disturbance uniformly. The ability to reject the load disturbance effectively is important, especially for critical thermal process like PEB.

The type of semiconductor substrates used for baking also has a significant impact on the type of load disturbance. The two most common substrates are silicon wafers and quartz photomasks (reticle). These substrate have very different geometries. Wafers have circular cross section, and typical dimensions are 200 mm diameter (approximately 8 inches) and 0.7 mm thick; or 300 mm diameter (approximately 12 inches) and 1 mm thick. Reticles have a square cross section and typical dimensions are 6×6 inches by 0.25 inches thick. This difference in geometry leads to a significant difference in mass that manifests itself as a difference in the time scale for baking. Due to its larger thermal mass, the loading effects due to a reticle is also more serious and takes a longer time to recover to set-point.

There is usually an error budget (Braun, 1998) associated with the processing of the reticle. As the reticle goes through many processing steps, errors introduced in each step leads to error in the final critical dimension. For a specified error tolerance, large errors in other processing steps can be compensated by reducing the temperature errors introduced in the baking step.

In this paper, we address the load disturbance caused by the placement of a reticle on a commercial bake plate. The load disturbance rejection is achieved by implementing a feedforward control strategy to minimize the worst case deviation from the nominal temperature set-point using linear programming. An order of magnitude improvement in the integrated square error is achieved using the optimal predictive controller as compared to a feedback only controller. This paper is organized as follows. The design of the optimal feedforward controller is shown in Section 2. Section 3 presents the experimental results. Finally, conclusions are given in Section 4.

2. OPTIMAL FEEDFORWARD CONTROL

In this section, we present the control strategy to compensate for the load disturbance induced by the placement of the cold substrate on the bake plate. Our approach will be to design a controller that, as best as possible, eliminates the load disturbance. Figure 2 shows the proposed control system where $G_c(s)$ is the controller, $G_p(s)$ is the plant, u_{fb}, is the feedback control signal, u_{ff}, is the feedforward control signal. The disturbance, $d(t)$, denotes the temperature change resulting from heat removed from the plate by placing the cold wafer on the bake plate. The bake plate temperature due to the heat supplied by the heater to the bake plate is denoted by $y(t)$. We note that the effect of the disturbance on the temperature of the bake plate can be eliminated if the bake plate temperature $y(t)$ is equal to the negative of the disturbance $d(t)$. This can be accomplished without feedback control by adjusting the heater power according to the relation

$$u(s) = u_{ff}(s) = -G_p^{-1}(s)d(s) \tag{1}$$

which results in a non-causal feedforward control move resulting in control moves before the actual placement of the substrate. We also note here that if there is a time delay in the heater power effect on plate temperature, the length of predictive control action will be increased.

In practice, there will be bounds placed on the achievable input power from the heater. The control signal is subjected to saturation within lower and upper bounds, for example $u \in [0, U^{max}]$. In this case, we will not be able to generate the desired $y(t)$ if the required input power is outside the achievable bounds. A simple implementation strategy would be to calculate the perfect control move as given by Equation (1), and then truncate at the boundaries. However, for our application we consider the optimal solution. To implement a practical solution, we discretize the problem in sampled data format, denoting the sampling indices as $k \in \{0, 1, ...\}$, and express the goal to minimize the maximum absolute error (Edgar *et al.*, 2001) as represented by the objective function

$$\min_{u(k)\in[0,U^{max}]} \; \max_{k\in\{0,1,\ldots,N\}} |y(k) + d(k)| \tag{2}$$

with the condition that the input is within prespecified limits and the desired output temperature remains equal to its initial steady-state condition over a time horizon N.

This optimization problem can be solved computationally by use of the model. The transfer function of the plate relating the bake plate temperature (output) and the input heater power (input), is now directly represented as an auto-regressive model with exogenous input (Goodwin and Sin, 1984)

$$A(q^{-1})y(k) = B(q^{-1})u(k) \tag{3}$$

where q^{-1} is the backward shift operator ($q^{-1}y(k) = y(k-1)$), and

$$A(q^{-1}) = 1 + a_1 q^{-1} + ... + a_n q^{-n} \tag{4}$$

$$B(q^{-1}) = (b_0 + b_1 q^{-1} + ... + b_n q^{-n})q^{-n_d} \tag{5}$$

where q^{-n_d} denotes any possible time delay and the order of the polynomials, n, have been assigned to be equal. The coefficients of this model can be related to the continuous time representation after discretization.

This discrete representation can also be expressed in a convolution model at sample time k,

$$y(k) = \sum_{j=0}^{k} c_j q^{-j} u(k - n_d) \tag{6}$$

where the coefficients are given by

$$c_j = b_j - \sum_{\ell=1}^{n} a_\ell c_{j-\ell}$$

Over a finite interval, N, the input and output signals can be represented as finite–dimensional vectors. The solution between the input and output vectors over the interval N can be expressed as a Toeplitz matrix,

$$\mathbf{Y} = \Psi \mathbf{U}$$

where

$$\mathbf{Y} = \begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N) \end{bmatrix}, \qquad \mathbf{U} = \begin{bmatrix} u(0 - n_d) \\ u(1 - n_d) \\ \vdots \\ u(N - n_d) \end{bmatrix}$$

$$\Psi = \begin{bmatrix} c_0 & 0 & \ldots\ldots & 0 \\ c_1 & c_0 & 0 \; \ldots & 0 \\ \vdots & & & \\ c_N & c_{N-1} & \ldots \; c_1 & c_0 \end{bmatrix}$$

The optimization problem of Equation (2) is equivalent to the following linear programming problem (Edgar *et al.*, 2001):
Minimize

$$\begin{bmatrix} 0 & \ldots & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ e \end{bmatrix} \quad \text{objective function} \tag{7}$$

subject to

$$\begin{aligned} \begin{bmatrix} \Psi & -\mathbf{1}_I \\ -\Psi & -\mathbf{1}_I \end{bmatrix} \begin{bmatrix} \mathbf{U} \\ e \end{bmatrix} &\leq \begin{bmatrix} -\mathbf{D} \\ \mathbf{D} \end{bmatrix} \quad \text{dynamic model} \\ \mathbf{U} &\leq U^{max} \\ \mathbf{U} &\geq 0 \\ y(k) + d(k) &= 0 \qquad k \in [n_f, ..., N] \end{aligned}$$

where the disturbance is to be eliminated from n_f to N. $\mathbf{1}_I$ is a column vector with all I entries equal to one, $e(k) = y(k) + d(k)$, and $\mathbf{D} = [d(0) \quad d(1) \ldots d(N)]'$. For vectors $\mathbf{v}$ and $\mathbf{w}$, $\mathbf{v} \leq \mathbf{w}$ means every entry of $\mathbf{v}$ is less than or equal to the corresponding entry of $\mathbf{w}$. U^{max} is the upper control signal saturation while the lower control signal situation is zero. The value of n_f is chosen such that n_f is feasible and n_{f-1} is not. This value is then chosen as the minimum time for eliminating the disturbance.

3. EXPERIMENTAL RESULTS

In this section, the feedforward control strategy is implemented for the baking of quartz photomasks (reticle). The bake plate used for the baking of reticle is shown in Figure 3. A detailed description of the bake plate is given in Schaper et al. (Schaper *et al.*, 1999*b*). A PID feedback controller is used for temperature control. Temperature sensing is achieved through a RTD (resistance temperature device) located within 0.050 inches to the plate surface. The control signal has a range of $0-10\ V$. The experiments were conducted at a setpoint of $90^\circ C$ with a sampling and control interval of 0.2 seconds for the bake plate. This temperature corresponds to a typical soft-bake condition for photoresist processing (Sheats and Smith, 1998), for example, Shipley $UVN2^{TM}$ negative DUV photoresist (Shi, 1998).

The disturbance from placing the reticle on the bake plate is determined as follows. First, the control signal is fixed by putting the controller in manual mode. A 6×6 inch reticle at around room temperature ($\approx\ 24^\circ C$) is then placed on the bake plate. The resultant temperature disturbance can then be modeled as the output of a transfer function with an appropriate input. By fitting the experimental data in the least square sense, a transfer function can be estimated. Figure 4 shows the disturbance to the temperature of the bake plate when a 6×6 inch reticle at room temperature is placed on it. The least square estimate with the input as a step is given by

$$G_d(q) = \frac{-0.0814}{1 - 1.5312q^{-1} + 0.5382q^{-2}}$$

For the identification of the bake plate model, a pseudo random binary sequence (Landau, 1990) is injected into the bake plate as shown in Figure 5, the following least square fit is obtained.

$$G_p(q) = \frac{0.0037}{1 - 2.11q^{-1} + 0.78q^{-2} + 0.83q^{-3} - 0.50q^{-4}}$$

Given the model of the plant and of the disturbance, the optimal feedforward control signal obtained from the linear programming formulation outlined in the previous section with constraint $-0.5\ V \le u_{ff}(k) \le 9.5\ V$ $\forall\ k \in \{0,1,\ldots,N\}$ was computed where the feedback signal at steady–state condition was $u_{fb} = 0.5\ V$. The feedforward signal is shown in Figure 6. Note that the control heater is brought to its maximum level and then its minimum level in a bang–bang control type fashion. This type of response and prediction would be difficult to determine using a trial-and-error hand-tuning method without the use of a model.

Figure 7 gives the comparison for the cases with and without feedforward control when a 6×6 inch reticle is placed on it. Good repeatability is seen. Notice that with feedback control only, the drop in bake plate temperature is $\approx 3.5^\circ C$ as compared to the case with feedforward control where the temperature drop is $\approx 0.5^\circ C$. The integrated square error (ISE) for the three cases are 3.25, 1.63 and 99.66. Using the optimal feedforward controller, the ISE was improved by about 30 times.

4. CONCLUSIONS

A feedforward control scheme has been designed and demonstrated to minimize the loading effects induced by placement of a cold substrate on a bake plate. The eliminations of these effects is important to current and future generation of DUV photoresists which are extremely sensitive to temperature variations. Of more importance is the improvement in the thermal budget. For a specific thermal budget, larger thermal errors in other processing steps can now be accommodated due to a reduction in temperature errors in the baking step. The control strategy is based on a linear programming method of minimizing the worst-case deviation from a nominal set-point during the load effects. Experimental results are performed for baking of a reticle. A 30% improvement in the integrated-square temperature error between the predictive controller and the feedback controller is achieved.

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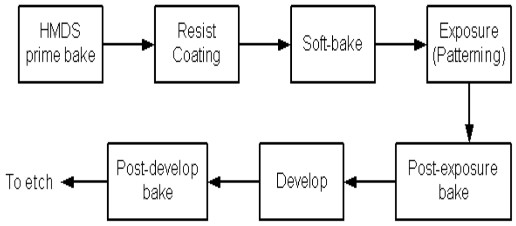

Fig. 1. Typical lithography sequence.

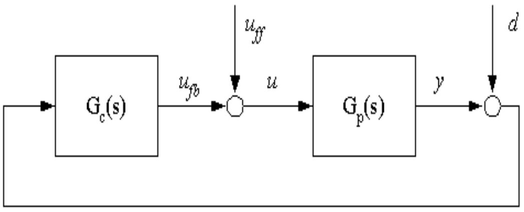

Fig. 2. Control system block diagram.

Year of First Product Shipment	1999	2001	2004	2007	2010
Technology Node (nm)	180	130	90	65	45
Post-Exposure Bake sensitivity (nm/^{0}C)	5	4	2	2	1

Table 1. Product Critical Level Post-Exposure Bake Requirements.

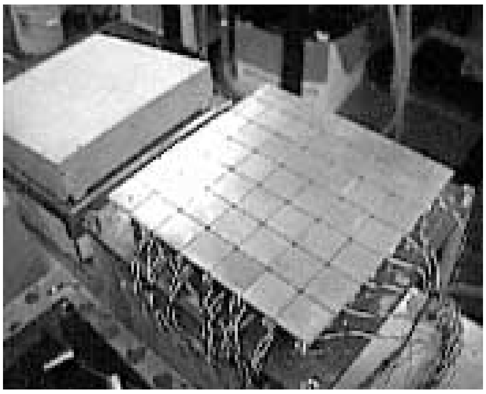

Fig. 3. Commercial bake plate.

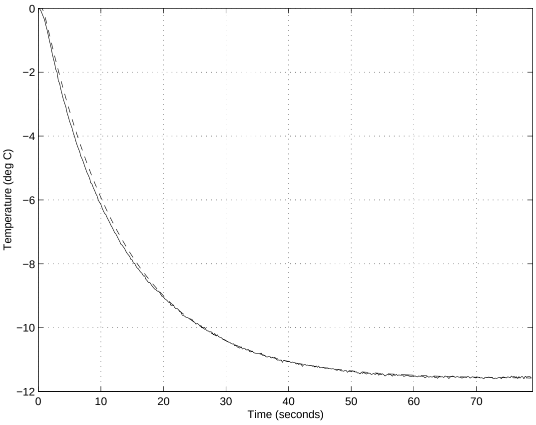

Fig. 4. The disturbance to the temperature of bake plate when a reticle at room temperature is placed on it. The dashed line is the least square estimate.

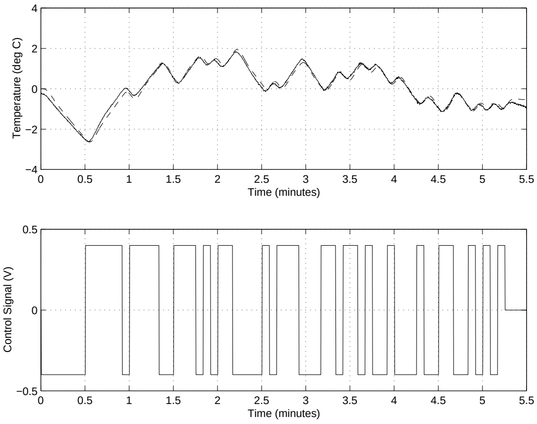

Fig. 5. Identification of bake plate. Dashed line is the least square estimate. Mean values have been subtracted.

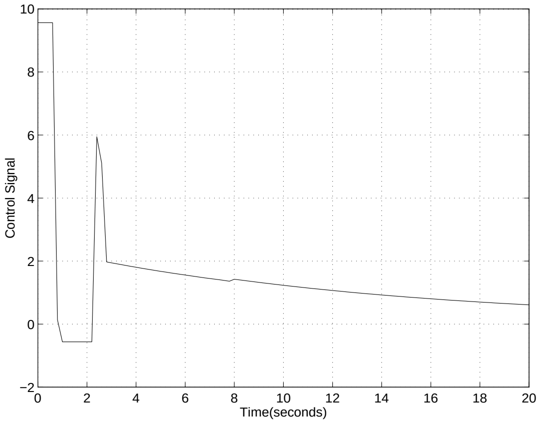

Fig. 6. The feedforward control signal obtained from linear programming.

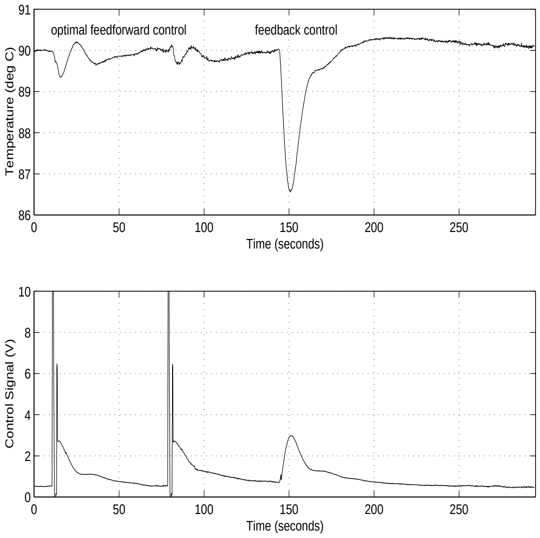

Fig. 7. The comparison between disturbance to the temperature of the bake plate. The first two runs are for optimal feedforward control; the last run is for the feedback control only.