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Adaptive Modeling and H_∞ Control for Photolithography Manufacturing Process

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***Abstract*— A run-by-run feedback controller is designed for Intel manufacturing fabs to stabilize the critical dimension in the process of photolithography, in the presence of unpredictable process drift and unknown non-Gaussian disturbances. The controller is a combination of an adaptive model with an H_∞ feedback.**

I. INTRODUCTION

Semiconductor manufacturing lines consist of a variety of different equipment. Each one has its own local controller. Although most parameters are controlled by local controllers at their desired values, some parameters, such as dose and focus in a process of photolithography, must be adjusted in a run-to-run control mode during manufacturing. This research is to design an outer loop, run-to-run controller for the purpose of critical dimension (CD) control. The study is conducted specifically for the manufacturing process of photolithography carried out in the fabs of Intel Corporation.

Considerable work has been done in the literature on the modeling and control of photolithography process ([1]-[4]). However, multi-variable adaptive modeling and H_∞ control are not used by semiconductor industry. In this paper, we study the possibility of developing run-to-run multiple-input feedback controller using real date from Intel manufacturing fabs. The research takes the view angle as a user of semiconductor equipments, not the designer of such equipments. The work consists of two parts, adaptive modeling and stabilizing feedback design.

II. MODELING

While off-line experimental data or DOE can be used to model the process of photolithography, the model does not reflect dynamic environmental changes of real manufacturing systems. Different makers and different models of equipments are used in manufacturing fabs. Unknown disturbances, such as machine aging and chemical contamination, cause process drift and unpredictable sudden shift in the output of a system. We believe that on-line adaptive modeling based on real-time data in manufacturing process is inevitable to improve CD stability. For this reason, the model developed in this paper is adaptive in the sense that model coefficients are updated after each run using the new input-output data. It is a discrete-time model based on real data from the shallow trench isolation area in one of the Intel flash manufacturing fabs.

Based on a study of all factors of the manufacturing process, we determined that the inputs of the system include at least the following parameters: dose (D), focus (F), nitride thin film thickness (T_1), and pad oxide thickness (T_2). The process outputs consist of nested and isolated CD and derived focus indicators. While the method developed in this paper is applicable to MIMO systems, we use nested CD as the only output in our simulations.

The model of a photolithography process is a nonlinear function in which $CD(k)$, the CD output of the kth run, is determined by the values of $(CD(k-1), D(k), F(k), T_1(k), T_2(k), W(k))$ where $W(k)$ represents random noise, D and F are control parameters that have relatively large influence on the CD output. The thickness measurements T_1 and T_2 have relatively small influence. They are feed-forwarded from previous operation steps and they are not controllable in litho operation. The output of the system is CD. We can approximate the model using its linearization. However, due to the reason discussed above, the coefficients in the model must be adaptive based on the data collected during the manufacturing process, i.e. the coefficients in the input-output function are updated using the most recent input and output data recorded during the manufacturing process. The model in this paper has the following form,

$$\begin{aligned} CD(k) &= a_0(k) + a_1(k)CD(k-1) + a_2(k)D(k) + \\ &+ a_3(k)F(k) + a_4(k)T_1(k) + a_5(k)T_2(k) + W(k) \end{aligned} \tag{1}$$

Note that $a_i(k)$ is an over simplified notation because $a_i(k)$ is not uniquely determined by k. The value of $a_i(k)$ is determined by the history of CD, D, F, T_1 and T_2. Therefore, $a_i(k)$ is actually a function of the past inputs and outputs. As a result, the equation (1) is a nonlinear system. The input and output values from a manufacturing line are collected in a matrix B. In the data matrix, each row consists of a set of input and output data from a specific run. The adaptive modeling starts from a matrix B_0, a set of existing data from either experiment or earlier manufacturing process. It is used to determine the values of $a_0(1), a_1(1), \cdots, a_5(1)$. After the first run, a set of new data is collected. It forms a row in the data matrix. As a result, B_1 is obtained by adding the row to the matrix B_0. A time window K can be set so that the number of rows in B_k is bounded by K. Old data are simply removed from the data matrix when a new row is added into the matrix. Then, the coefficients $a_0(2)$, $a_1(2), \cdots, a_5(2)$ are estimated based on B_1 using linear regression. Update the estimation during the manufacturing process every time a new set of data becomes available. It makes the model adaptive to unknown variations in the system. This process is applied to a set of real data with a total of 98 runs. In CD prediction, we use the model obtained from B_k to predict $CD(k+1)$. The relative error of the CD prediction for this set of data is

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bounded by $\pm 3\%$ (See Figure 1). The values of $a_2(k)$ and $a_3(k)$, the two coefficients of control inputs, are shown in Figure 2. It shows that the system has two large changes when k is in $[20, 25]$, and $[75, 85]$.

III. RUN-TO-RUN FEEDBACK CONTROL

Based on the model a feedback controller is designed to stabilize the critical dimension. In semiconductor manufacturing processes, little is known about the many factors affecting CD in real-time. To achieve robust performance, we use H_∞ control theory to derive a feedback that stabilizes the CD output and minimizes the influence of unknown disturbance on the CD variation. The feedback controller has the following form,

$$[D(k)\ F(k)]^T = \alpha(CD(k-1), a_0(k), \cdots, a_5(k), T_1(k), T_2(k))$$

After each run, the new data from the system is used to update the model as described in Section II. Then, the values of control input for the next run is computed using $\alpha(\cdot)$ based on the updated model and the new thickness measurements T_1 and T_2. The function $\alpha(\cdot)$ consists of two parts, $\alpha(\cdot) = \alpha_o(\cdot) + \alpha_s(\cdot)$. The purpose of α_0 is to define the operating point of the system at the desired CD value. It is defined by the following equation,

$$\begin{aligned} \alpha_0 = & (CD_{desire} - (a_0(k) + a_1(k)CD_{desire} + \\ & (a_4(k)T_1(k) + a_5(k)T_2(k))) \begin{bmatrix} \rho/a_2(k) & (1-\rho)/a_3(k) \end{bmatrix}^T \end{aligned}$$

where ρ takes values in the interval $[0, 1]$. It is the weight on the control inputs. A large value of ρ implies the dose D takes more "responsibility" in the control.

The function α_s is a stabilizing controller. In this study, we adopt the H_∞ method to design the controller $\alpha_s(\cdot)$. Following ([5]), the feedback is designed so that the L_2-gain from disturbance W to CD error is bounded by a given number γ. It means that the ratio between the output "energy" and noise "energy" is bounded by γ.

$$\alpha_s(k) = \begin{bmatrix} -0.0002 & -0.0011 \end{bmatrix}^T (CD(k-1) - CD_{desire})$$

IV. SIMULATIONS

Process drift is a common phenomenon in manufacturing process due to uncertain reasons, such as continuous wear of equipments, normal consumption of material and the environmental chemical contamination. In the simulation, the plant model of photolithography is a linear regression model based on a set of real data. In addition, a drift function is integrated into the plant model. As illustrated in Section II, the control value is computed using adaptive model that is updated based on the values of $CD(k-1)$, $D(k-1)$, $F(k-1)$, $T_1(k-1)$, and $T_2(k-1)$. Then, the update model and the values of $T_1(k)$ and $T_2(k)$ are used by the controller to compute the control input α_0 and α_s. In the simulation, $\rho = 0.8$. Therefore, more weight is put on the dose. The H_∞ gain is $\gamma = 1.1$. Without control, the drift effect is shown in the first graph of Figure 3. After 200 runs, the relative CD error is drifted by about 4%. With feedback control based on adaptive model, the drift problem is under control (Second graph in Figure 3). The history of control inputs, $D(k)$ and $F(k)$, is shown in Figure 4. The control input is relatively smooth when $t < 60$ runs because the drift is small at the beginning. The magnitude of control inputs becomes higher as the drift increases. In the simulation, we use both D and F as control inputs. It helps to reduce the magnitude of D comparing to the case when D is used as the only control input.

V. CONCLUSION

Adaptive modeling and H_∞ control are applied to the real data from shallow trench isolation in one of the Intel flash sites for the purpose of CD stabilization. Without using any physical model of individual equipment, algorithm and design method are developed for outer loop model and feedback control of manufacturing lines with drift and unknown disturbances. According to simulations based on real data from Intel manufacturing lines, the algorithm and design method is promising in real applications.

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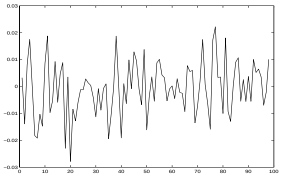

Figure 1: Relative error of CD prediction

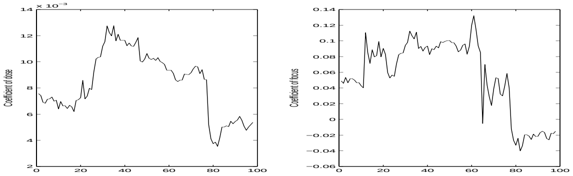

Figure 2: The history of $a_2(k)$ and $a_3(k)$

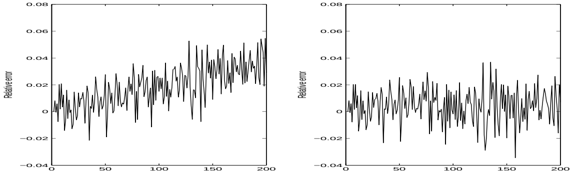

Figure 3: Relative error of CD

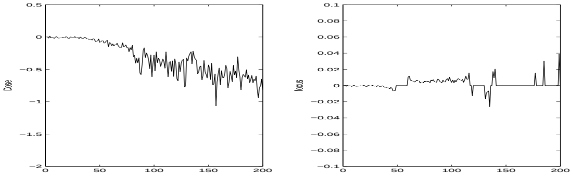

Figure 4: Control inputs in the second simulation