Nonlinear Run-to-Run
Controller for Semiconductor Manufacturing

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Run-to-run control is a generic methodology in control of semiconductor manufacturing processes. It is a model based process control strategy whereby process inputs (recipes) are adjusted on a run-to-run basis in response to measurements (responses) of process state variables. It updates the recipes of the process at the beginning of each run. In semiconductor manufacturing, many processes are subjected to small drifts or shifts. If the perturbations are small enough, they can be compensated successfully using the exponential weighted moving average (EWMA) method. But, unfortunately, this is not always the case. For example, many plasma processes have been shown to exhibit small to large non-linearity in behavior. Furthermore, the photoresist process and the chemical mechanical processing (CMP) process require dynamic process models too. Thus it is hard to use a linear model to approximate the process and necessary to develop nonlinear algorithms to solve this type of problems.

We developed the set-valued run-to-run controller (SVA) to control nonlinear processes. Different from other conventional RtR controllers, it is applicable for various types of noises and disturbances, which are present in real industrial processes. Furthermore, it is robust to model errors and sensor errors. The SVA combines the set-valued method with the ellipsoid algorithm and tracks the process model in each run for multi-targets. Nonlinear algorithm in RtR control is usually very complex and requires intensive computing. Moreover, exact estimation of the process parameter set is an NP-hard problem. The ellipsoid algorithm is easily applicable and provides an approximate minimum bound on the parameter sets. Identifying the process model within the parameter set makes the identification reliable and efficient. Recent developments of the ellipsoid algorithm and set-valued method inspired the development of the SVA. With respect to the conventional recursive methods like recursive least squares (RLS), the ellipsoid algorithms, such as optimal bounding ellipsoid (OBE) and optimal volume ellipsoid (OVE), offer a feasible set for model updating, superior adaptation, efficient use of innovation data, robustness to model error and measurement noises and improved computational efficiency.

To test the SVA controller, both linear and nonlinear semiconductor manufacturing processes were simulated under various conditions. The processes are real industrial processes derived from engineering practice. We illustrate it by the following examples: 1. LPCVD process under large model error. 2. LPCVD process under drift (Compared with the EWMA controller). 3. LPCVD process under shift (Compared with the EWMA controller). 4. Photoresist process under drift. 5. Photoresist process under shift. In linear case, the performance of SVA controller is comparable to the EWMA controller under drift. It is better than the EWMA controller under shift or large model errors. In nonlinear case, the SVA controller can successfully control second order or higher order nonlinear processes when it is hard for a linear RtR controller to do.

Comparative evaluation of RtR controllers demonstrates superb performance of the SVA controller. However when the non-linearity of the processes is severe, the SVA may not control the process well either. It’s still an open field and waiting for us to solve.

Introduction

Run-to-run control is a generic methodology in control of semiconductor manufacturing processes. It is a model based process control strategy whereby process inputs (recipes) are adjusted on a run-to-run basis in response to measurements (responses) of process state variables. It updates the recipes of the process at the beginning of each run. In semiconductor manufacturing, many processes are subjected to small drifts or shifts. If the perturbations are small enough, they can be compensated successfully using the exponential weighted moving average (EWMA) method. But, unfortunately, this is not always the case. For example, many plasma processes have been shown to exhibit small to large non-linearity in behavior. Furthermore, the photoresist process and the chemical mechanical processing (CMP) process require dynamic process models too. Thus it is hard to use a linear model to approximate the process and necessary to develop nonlinear algorithms to solve this type of problems.

Design and Benefits of the SVA

We developed the set-valued run-to-run controller (SVA) to control nonlinear processes. Different from other conventional RtR controllers, it is applicable for various types of noises and disturbances, which are present in real industrial processes. Furthermore, it is robust to model errors and sensor errors. The SVA combines the set-valued method with the ellipsoid algorithm and tracks the process model in each run for multi-targets. Nonlinear algorithm in RtR control is usually very complex and requires intensive computing. Moreover, exact estimation of the process parameter set is an NP-hard problem. The ellipsoid algorithm is easily applicable and provides an approximate minimum bound on the parameter sets. Identifying the process model within the parameter set makes the identification reliable and efficient. Recent developments of the ellipsoid algorithm and set-valued method inspired the development of the SVA. With respect to the conventional recursive methods like recursive least squares (RLS), the ellipsoid algorithms, such as optimal bounding ellipsoid (OBE) and optimal volume ellipsoid (OVE), offer a feasible set for model updating, superior adaptation, efficient use of innovation data, robustness to model error and measurement noises and improved computational efficiency.

Simulation

To test the SVA controller, both linear and nonlinear semiconductor manufacturing processes were simulated under various conditions. The processes are real industrial processes derived from engineering practice. We illustrate it by the following examples: 1. Light pressure chemical vapor deposition (LPCVD) process under large model error. 2. LPCVD process under drift (Compared with the EWMA controller). 3. LPCVD process under shift (Compared with the EWMA controller). 4. Photoresist process under drift. 5. Photoresist process under shift. In linear case, the performance of SVA controller is comparable to the EWMA controller under drift. It is better than the EWMA controller under shift or large model errors. In nonlinear case, the SVA controller can successfully control second order or higher order nonlinear processes when it is hard for a linear RtR controller to do.

The process model for LPCVD process:

$$\hat{R}_1 = \exp(c1 + c2 \cdot \ln P + c3 \cdot T^{-1} + c4 \cdot Q^{-1}) + d1$$

$$\hat{R}_2 = \hat{R}_1 \left[\frac{1 - S \cdot C_{gs} \hat{R}_1 Q^{-1}}{1 + S \cdot C_{gs} \hat{R}_1 Q^{-1}} \right] + d2$$

Where R_1 and R_2 are the deposition rates in Angstroms/minute on the first and the last wafer separately; d_1 and d_2 are drifts.

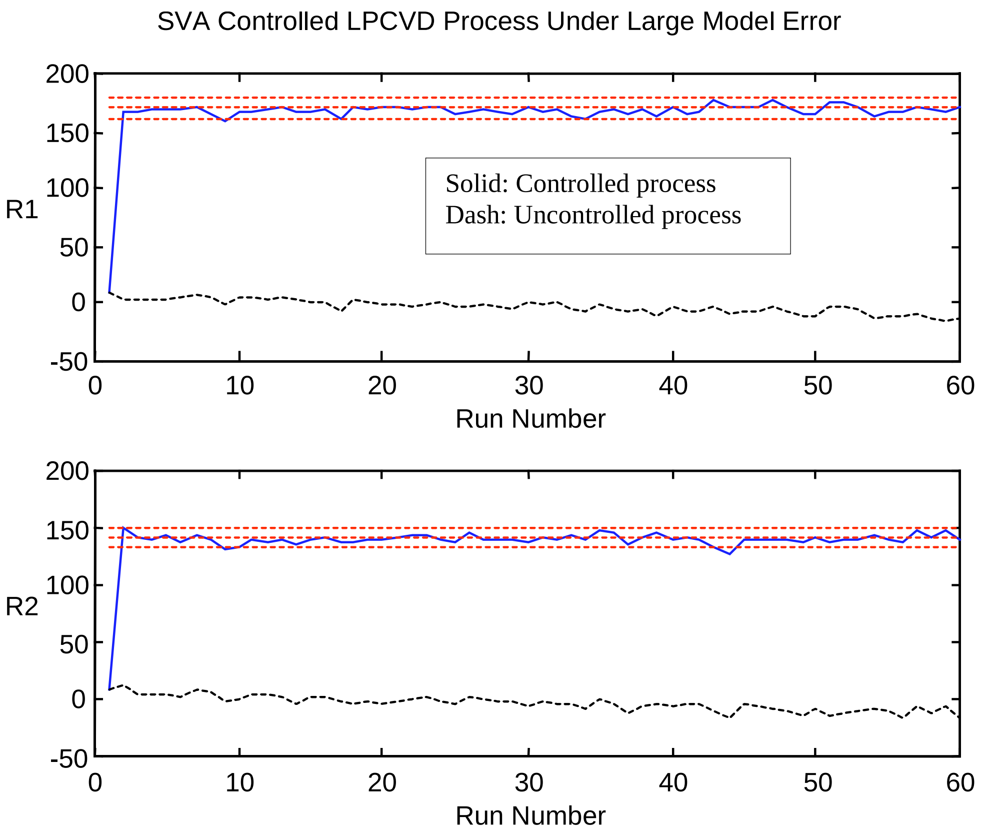
The process model for photoresist process:

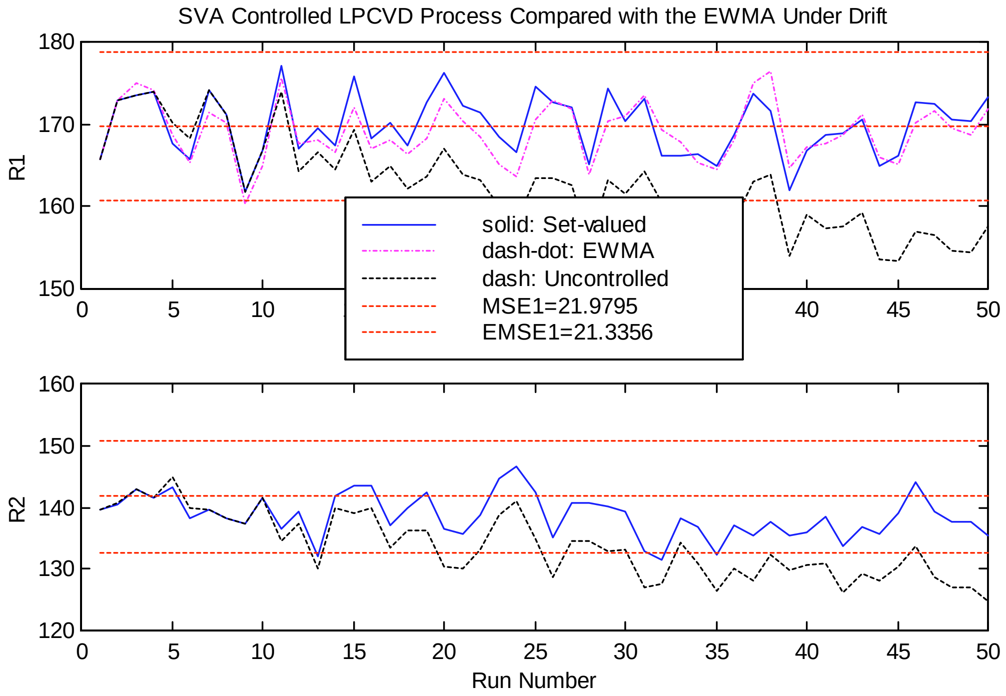
$$T = -13814 + \frac{2.54 \times 10^6}{\sqrt{SPS}} + \frac{1.95 \times 10^7}{BTE \cdot \sqrt{SPS}} - 3.78BTI - 0.28SPT - \frac{6.16 \times 10^7}{SPS}$$

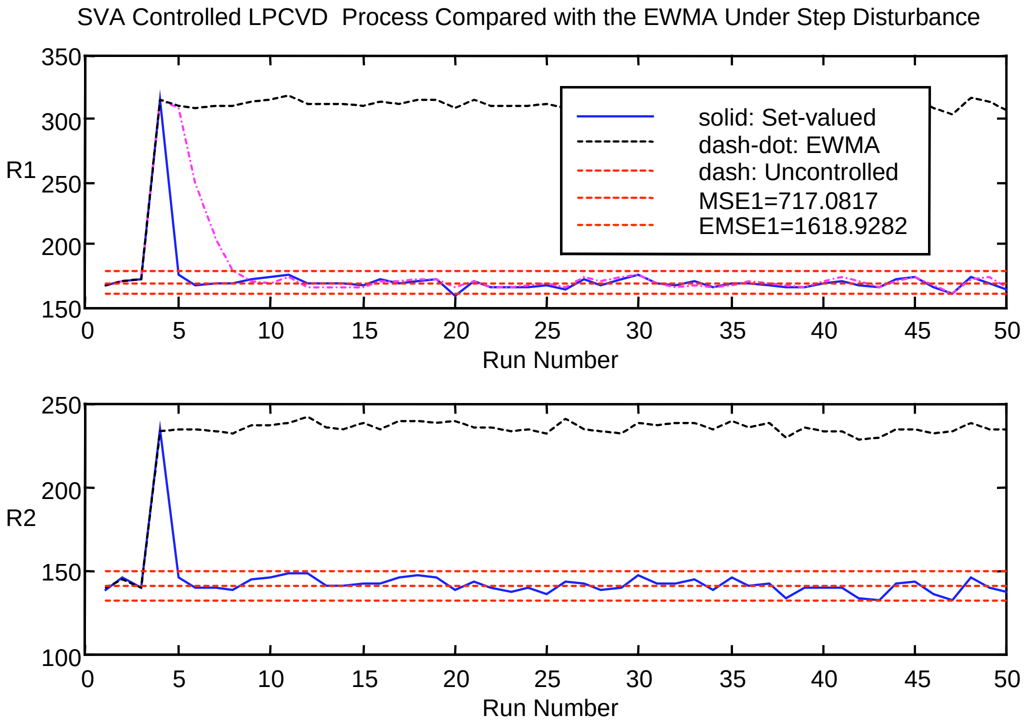
Where T is the resist thickness in Angstroms, SPS the spin speed in RPM, SPT the spin time in seconds, BTI the baking time in seconds, and BTE the baking temperature in degrees Celsius.

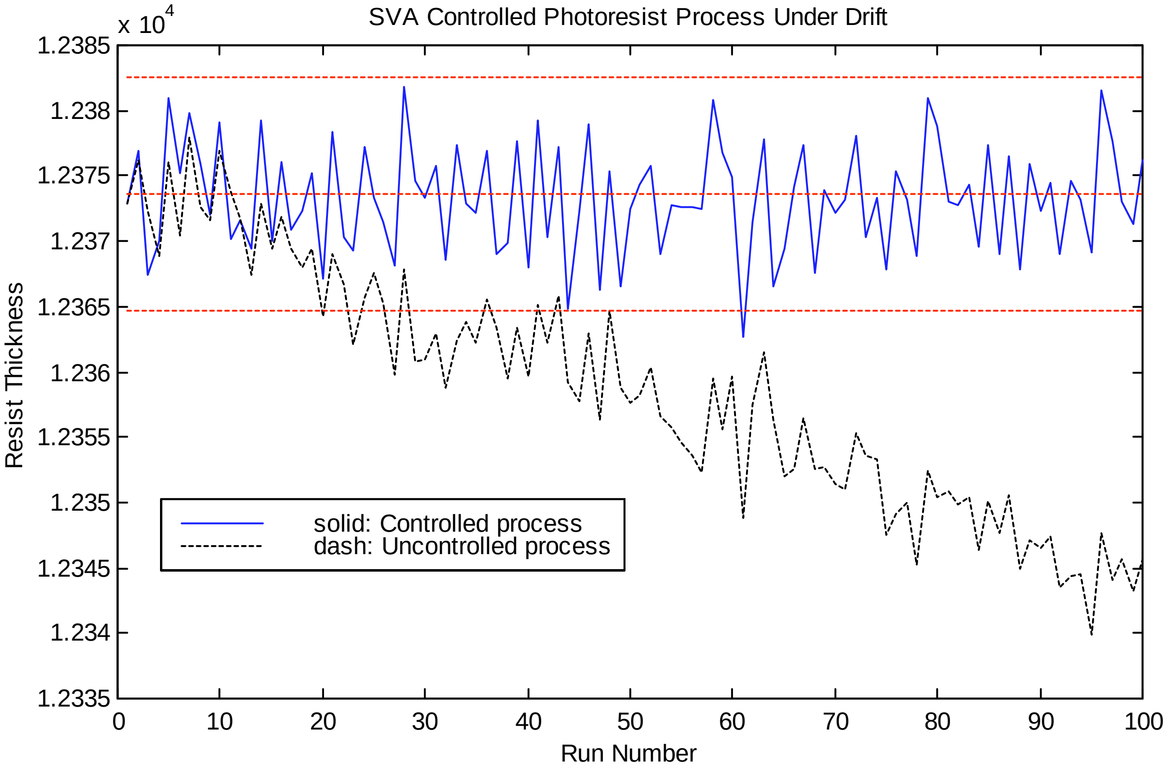
Conclusions

Comparative evaluation of RtR controllers demonstrates superb performance of the SVA controller. However when the non-linearity of the processes is severe, the SVA may not control the process well either. It is still an open field and waiting for us to solve.

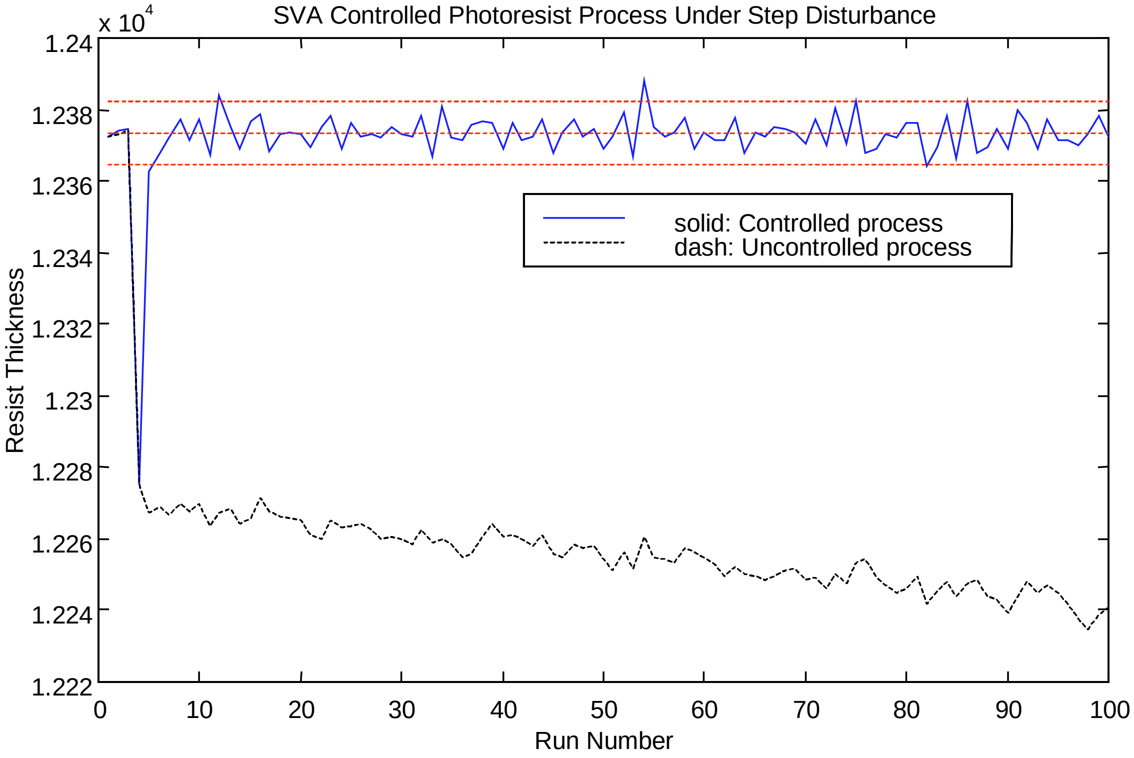

SVA Controlled LPCVD Process Under Large Model Error


SVA Controlled LPCVD Process Compared with the EWMA Under Drift
R1
180
170
160
150
0
5
10
40
45
50
solid: Set-valued
dash-dot: EWMA
dash: Uncontrolled
MSE1=21.9795
EMSE1=21.3356
R2
160
150
140
130
120
0
5
10
15
20
25
30
35
40
45
50
Run Number


SVA Controlled LPCVD Process Compared with the EWMA Under Step Disturbance
350
300
R1
250
200
150
0
5
10
15
20
25
30
35
40
45
50
Run Number
solid: Set-valued
dash-dot: EWMA
dash: Uncontrolled
MSE1=717.0817
EMSE1=1618.9282
250
200
R2
150
100
0
5
10
15
20
25
30
35
40
45
50
Run Number



SVA Controlled Photoresist Process Under Drift



SVA Controlled Photoresist Process Under Step Disturbance