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Technical paper

Coordination and control of batch-based multistage processes

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ABSTRACT

Run-to-run (R2R) process control has attracted much attention in research and has been widely used in practice. It has been proved effective at compensating for process disturbances by using R2R controllers at a single stage. However, most manufacturing processes span across multiple stages; variation in earlier stages can be magnified stage by stage if they are not properly eliminated. In addition, products are processed batch by batch in certain manufacturing processes. In such cases, the traditional EWMA controller might not effectively reduce the variation. This paper focuses on developing a process control strategy for batch production in a multistage process. In the newly proposed framework, a batch-allocation operation is introduced to group products into similar clusters before each stage; an R2R controller is then implemented to generate customized recipes for each batch. This framework emphasizes better coordination among the stages in a multistage process. Simulation results show that the proposed strategy is effective for the reduction of variation.

1. Introduction

In semiconductor manufacturing processes, products are always processed run by run. Each run is an undividable cycle within which measurements of quality results are unavailable. Process drifts and shifts can occur between different runs for many reasons, such as the tools wearing out, operators switching, the working conditions changing, and the machines becoming unstable. To compensate for these process drifts or shifts, run-to-run (R2R) process control methods have attracted extensive attention in quality control research and have been widely used in practice [1]. Such controllers usually use outputs from previous runs to generate optimal recipes for new runs, to seek better compensation for process disturbances and to achieve higher quality [2]. Because most manufacturing processes naturally span multiple stages, and variations in such multistage processes tend to propagate across stages [3], it is important to implement appropriate process control algorithms, coordinating inputs and outputs across multiple stages, optimizing recipes for each stage and minimizing the output variation [4].

Consider the wafer preparation process as an example. As shown in Fig. 1, there are almost ten major steps from crystal pulling to wafer packaging. Each stage takes the output from its preceding stage as its input and sends its output farther down, to its downstream stages. Thus, the deviations at one stage are transferred into subsequent stages; if no effective control actions are taken, then such deviations become larger and larger and could finally harm the quality of the finished products.

In the wafer preparation process, another important issue is that wafers are processed in batches with variable sizes. For example, a slicing run can generate 300 wafers. These wafers are put together and moved through the rest production stages. When these wafers reach the lapping stage, since the lapping machine can only handle 50 wafers each time (this is limited by the capacity of the lapping plate), these wafers have to be clustered into 6 batches and be processed sequentially. Similarly, when these 300 wafers reach the etching stage, since the capacity of the etching chamber is 100, these wafers need be clustered into 3 batches. Therefore, wafers must be grouped or un-grouped between stages to satisfy the batch size limitation of each stage.

This batch-based feature is in fact quite commonly seen in semiconductor manufacturing because of the equipment capacity constraint. Therefore, to achieve better quality in a multistage manufacturing process, the following two problems become critical:

(a) How to allocate products (wafers, in the example studied in this work) in appropriate batches so that the transmission of variation is minimized and the final product quality is optimized.
(b) How to design control strategies (generate optimal recipes) for each stage at each run by considering both the grouping information and the output information from previous runs.

Intuitively, unique opportunities exist in controlling a multistage process. For example, the bow of a wafer (defined in Fig. 2) measures its curvature. A wafer with a large bow value after slicing could be improved if a faster rotation speed is used in the lapping

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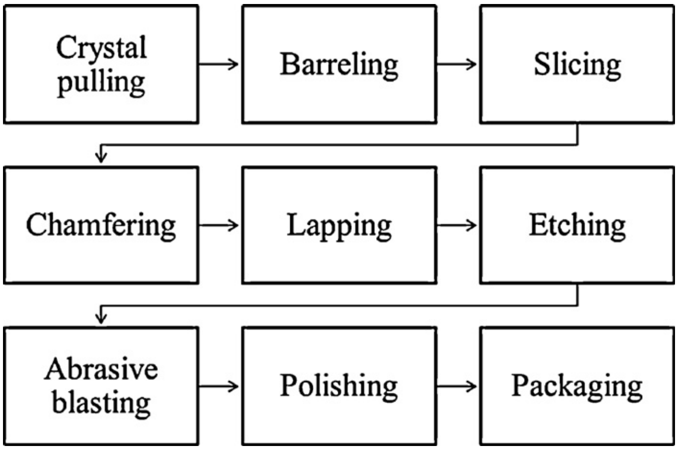

Fig. 1. The wafer preparation process.

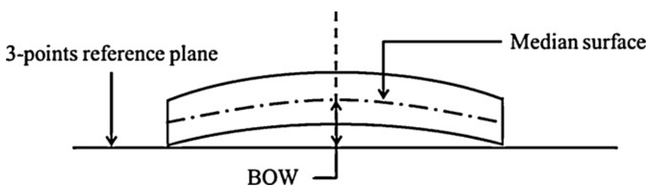

Fig. 2. Definition of "bow" for a wafer.

stage or less time is used in the etching stage. In other words, in a multistage process, there are opportunities for downstream stages to systematically compensate for deviations that resulted from upstream stages by using customized recipes. Therefore, the implementation of process control by considering the coordination of multiple stages is important in such a process.

The objective of this work is to develop a run-to-run process control framework for a multistage manufacturing process (MMP). In the multistage R2R control setting, the variation in the incoming information from an upstream stage could be treated as observable but uncontrollable noise that moves to a downstream stage. Such noises could be compensated by well-designed batch-allocation strategies and control actions. This idea is well illustrated in Fig. 3.

Compared to the conventional R2R control framework for a single stage, there are two key features in the framework in Fig. 3. First, a batch allocator is added to the model. The outputs from stage k, which have a large overall variation, are split into batches, each of which have a smaller variation, and are fed into stage $k+1$. The core of the batch allocator is a clustering algorithm for reducing *within-batch* variation. Second, the R2R controller equipped for each stage is updated to take batch information as one of its inputs. A customized recipe can be generated for each batch to reduce *batch-to-batch* variation. Therefore, the batch allocator makes it possible to have a finely tuned recipe, and an implementation of the R2R controller that is based on both the feedback and the feed-forward information is expected to be effective at reducing the propagation of variation.

The rest of the paper unfolds as follows. In Section 2, a literature review on the recent research that is relevant to R2R process control and multistage process modeling is first presented. In Section 3, the batch-based R2R control strategy for a single stage is shown. Section 4 extends the framework to a process having multiple stages. In Section 5, the performance of the proposed control framework is studied and is compared with an existing controller. Finally, Section 6 concludes this work with suggestions for future research.

2. Literature review on run-to-run control and multistage process modeling

Conventionally, R2R controllers have been designed to compensate for process disturbances in a single stage. Among others, the exponentially weighted moving average (EWMA) controller [5] and the double EWMA controller [6] have been extensively studied because of their simplicity and robust performance. Various extensions of these controllers also appear in the literature. Del Castillo and Hurwitz [1] provided a literature review of R2R control methods from a statistical and control engineering point of view and proposed a self-tuning controller based on the recursive least square estimation method to provide better control performance. Those control filters are all developed using quantitative rather than qualitative measurements. Wang and Tsung [7], Shang et al. [8], Wang and Tsung [9] and Lin and Wang [10] proposed an R2R control scheme that uses categorical measurements for process adjustment. However, most of the methods in the literature utilize a single-output model.

Tseng et al. [11] investigated the control of a multiple-inputs–multiple-outputs (MIMO) process using a multivariate exponentially weighted moving average (MEWMA) controller with a variable discount factor. The authors showed the feasible region and the approximate solution for the optimal discount factor. Del Castillo and Rajagopal [12] also extended the univariate double EWMA method to a MIMO double EWMA controller and pointed out that the performance of the MIMO controller is superior to that of several single-input–single-output (SISO) controllers. Fan and Wang [13] extended the EWMA controller based on a neural network online tuning approach for SISO models [14] to a double EWMA controller for MIMO models. Jen et al. [15] also focused

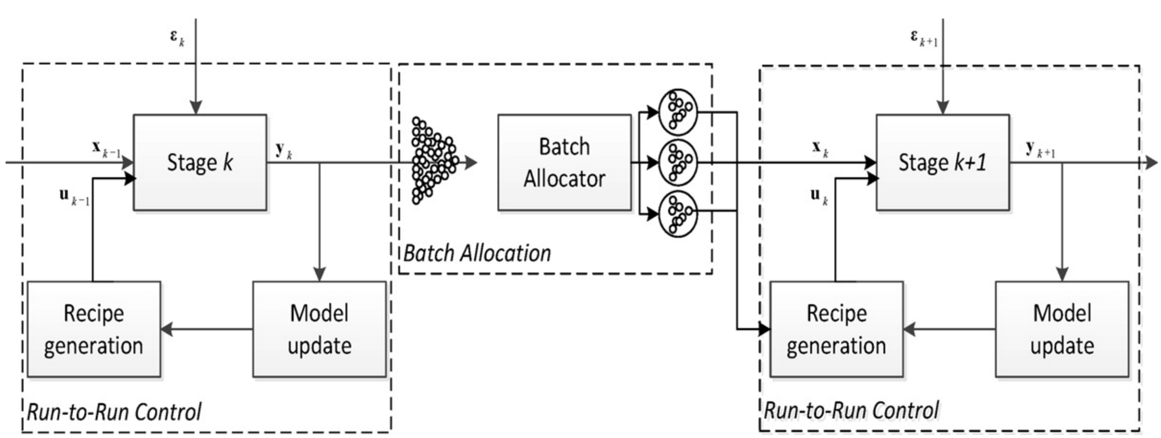

Fig. 3. A batch-based R2R control framework for multistage manufacturing processes.