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Cycle time analysis of dual-arm cluster tools for wafer fabrication processes with multiple wafer revisiting times

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ABSTRACT

For some wafer fabrication processes, the wafers need to visit some processing modules for a number of times, which is referred to as the revisiting process. With wafer revisiting, it is very complicated to analyze the cycle time of a dual-arm cluster tool. Due to the fact that atomic layer deposition (ALD) process is a typical revisiting process in the semiconductor industry, study is conducted on cycle time analysis of dual-arm cluster tools for the ALD process with multiple revisiting times. The system is modeled by a type of Petri net. With this model, it is revealed that the system may never reach a steady state. Based on this finding, a method is presented to analyze the cycle time and analytical expressions are derived to calculate the cycle time for different cases. Several illustrative examples are given to show the applications of the proposed approach.

1. Introduction

With a single-wafer processing technology that processes wafers one by one at a process module (PM), cluster tools are widely used to process wafers in semiconductor manufacturing. Such a tool can provide a flexible, reconfigurable, and efficient environment [1,2], which results in higher yield [19], shorter cycle time [17,19,24], better utilization of space [2,24], and lower capital cost [24]. In a cluster tool, there are several PMs, an aligner, a wafer handling robot, and loadlocks for wafer cassette loading/unloading. Raw wafers in the cassette are loaded into the system by the robot, delivered to one or more PMs for being processed in a specific order, and finally returned to the loadlocks. With a single or dual-arm robot, a tool is called single or dual-arm cluster tool as shown in Fig. 1.1(a) and (b), respectively.

In operating a cluster tool, it needs to schedule wafer processing and robot activities simultaneously, which makes the scheduling problem of a cluster tool very complicated. With two loadlocks in a cluster tool, after one cassette of wafers in one loadlock is being processed, another cassette of wafers can be loaded into the other loadlock. Thus, a cluster tool can be operated consecutively without interruption in a steady state at most of the time. To reveal the mechanism of operating a cluster tool, great efforts have been made in modeling and performance evaluation for cluster tools [3,7,20,21,25,34,38,43]. It is found that the operations of a cluster tool can be divided into two different regions: transport-bound and process-bound ones. In the former, the robot is always busy such that robot task time determines the cycle time of the system. In the latter, the robot has an idle time and the cycle time is determined by the processing time in the PMs. In a cluster tool, only after a wafer is loaded into a PM can the PM start its wafer processing. Thus, processing activities follow the robot tasks [23]. With these properties, dispatching or priority rules are developed to schedule robot tasks [9,25]. Because the robot moving time from one PM to another can be treated as a constant and is much shorter than the wafer processing time [12], backward scheduling is optimal for single-arm cluster tools [14,16]. For dual-arm cluster tools, a swap strategy is shown to be efficient [25], which simplifies robot tasks and reduces cycle time. Studies on scheduling cluster tools with wafer residency time constraints are conducted and efficient techniques are presented in [12,45–48].

All aforementioned studies are conducted for processes without wafer revisiting. However, in practice, some wafer fabrication processes are repeated processes, such as the atomic layer deposition (ALD) process. For such revisiting processes, it often requires exactly identical processing conditions for the revisiting operations. With wafer revisiting, a cluster tool is no longer a flow-shop such that it is deadlock-prone [13]. Thus, the results obtained for processes without revisiting are not applicable for the processes with revisiting. Scheduling cluster tools is somehow similar to hoist/robotic cells scheduling [10,4,5,8,6]. However, differences exist between them due to multiple PMs for each step, and unique chamber operation for wafer fabrication. It is well-known in the discrete event system

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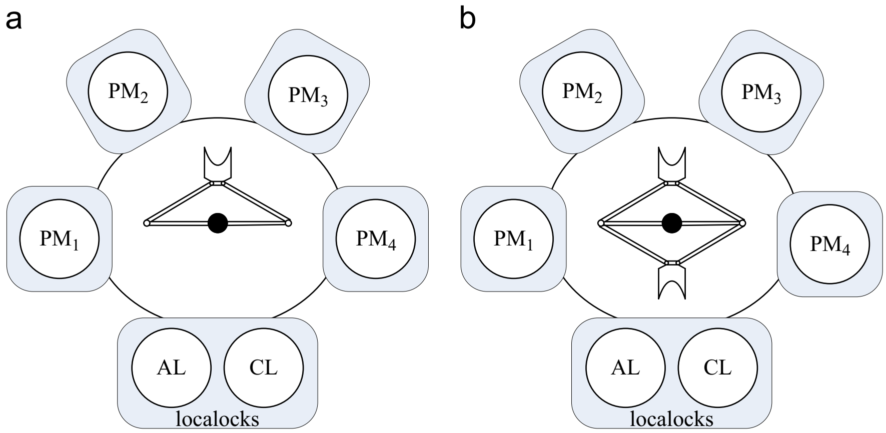

Fig. 1.1. The cluster tools: (a) single-arm robot; and (b) dual-arm robot.

community that, it is highly complicated to schedule such a system to obtain an optimal and deadlock-free schedule. Thus, it is very challenging to schedule cluster tools with wafer revisiting.

By considering the wafer revisiting process, Petri net models are developed for the performance evaluation in [34,44]. However, although the results obtained in [34,44] may be useful for a scheduling guide, it does not present a way to find an optimal and deadlock-free schedule. In order to solve such a problem, Lee and Lee [13] pioneer the study on scheduling cluster tools with wafer revisiting and develop a Petri net model for single-arm cluster tools with wafer revisiting. With the model, a mixed integer programming model is presented to find an optimal schedule in an exact way. Nevertheless, it involves prohibitive computation. To overcome this problem, the scheduling problem of single-arm cluster tools for the typical wafer revisiting process ALD is studied in [36]. With a deadlock-free Petri net model developed for it, an optimal schedule can be obtained by using analytical expressions. For dual-arm cluster tools with wafer revisiting, the scheduling problem is studied by using a swap strategy in [37,49]. It is found that, by using a swap strategy, the process may never reach a steady state and the cycle time obtained by using the methods presented in [34,44] is not correct for some cases. If a process requires performing some operations k times, such a process is called k-time revisiting. For a process with a two-time revisiting, an approach is presented to calculate the correct cycle time in [37].

However, a wafer fabrication process may require that the revisiting time are more than two. For example, in the ALD process, the number of wafer revisiting times may be up to more than five [13]. Hence, the results obtained in [37,49] are not enough. In [37,49], it is found that there are three local cycles and three global cycles for a process with a two-time revisiting, i.e., $k=2$. When the process switches from a local cycle to a global cycle or from a global cycle to a local cycle, there may be a transient process. It seems that the results obtained in [37] can be easily extended to the $k>2$ cases. However, after careful analysis of the $k>2$ cases, we find that, with $k>2$, there are more local cycles and the transient process becomes much more complex. In fact, as the revising time increases, the robot waiting time changing before swapping at the steps for the local cycles becomes much more complicated in the transient process as we see later. Hence, the problem of cycle time analysis is much more complicated than that in the $k=2$ case. Thus, the results obtained in [37] are no longer applicable and are not so easy to be extended as claimed. This motivates us to conduct this study on cycle time analysis for the general case that has multiple wafer revisiting times. The system is modeled by a Petri net (PN) and, with the model, analytical expressions are derived to calculate the cycle time. As far as the authors know, this is the first research report on this issue.

Our previous work shows that, for dual-arm cluster tools with wafer revisiting, the initial state has effect on the cycle time [22]. However, as pointed out there, the swap strategy used is different from ordinary swap strategy. As an ordinary swap strategy is widely used in the industry, it is meaningful to analyze the cycle time when the ordinary swap strategy is applied. Thus, in this paper, we focus on the swap strategy only.

In the next section, we briefly introduce the process and develop the PN model for a dual-arm cluster tool with wafer revisiting. Based on the model, cycle time analysis is conducted in Section 3 and analytical expressions are presented for the calculation of cycle time. Illustrative examples are used to show the applications of the proposed approach in Section 4. Finally, conclusion is presented in Section 5.

2. The process and Petri net modeling

Consider that ALD is a typical wafer fabrication process with wafer revisiting in the semiconductor manufacturing industry, the cycle time analysis conducted for dual-arm cluster tools in this work is based on the ALD process. However, the results obtained from this process are useful for other revisiting processes. In this section, we briefly introduce the process and develop a Petri net model for it.

2.1. The ALD process

To complete a wafer, a number of operations should be performed. If all operations are different and each operation is performed by different PMs, the process is a non-revisiting one, and otherwise some operations are performed by the same PM, it is a revisiting one. An operation is defined as a fabrication step if it is performed by a fabrication process with its unique process environment. In a cluster tool with the wafer revisiting process, a wafer needs to visit some steps more than once. For an ALD, it needs a wafer to visit some steps several times to control the thickness of the deposition layer. More specifically, it has three steps. A wafer visits Step 1 first, and then Step 2, followed by Step 3. After that, it goes to Step 2 again and then Step 3. Such a process is repeated for $k \geq 2$ times as shown in Fig. 2.1, where k is determined by a process plan. In cluster tools, more than one PM can be configured to perform an operation at a step. Thus, let m_i be the number of PMs for Step i, then the wafer flow pattern for ALD can be denoted as $(m_1, (m_2, m_3)^k)$ with $(m_2, m_3)^k$ being the revisiting process. Due to the fact that often when a wafer revisits a step, it requires the exactly identical processing conditions as it previously visited the step. Thus, in [37], the study is conducted for