듀얼블레이드 로봇 클러스터툴의 생산성 분석

Throughput Analysis for Dual Blade Robot Cluster Tool

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Abstract: The throughput characteristics of the cluster tool with dual blade robot are analyzed. Using equipment's cycle time chart of the equipment, simple analytic form of the throughput is derived. Then, several important throughput characteristics are analyzed by the throughput formula. First, utilization of the process chamber and the robot are maximized by assigning the equipment to the process whose processing time is near the critical process time. Second, rule for selecting optimal number of process chambers is suggested. It is desirable to select a single process chamber plus a single robot structure for relatively short time process and multi process chambers plus a single robot, namely cluster tool for relatively long time process. Third, throughput variation between equipments due to the wafer transfer time variation is analyzed, especially for the process whose processing time is less than critical process time. And the throughput and the wafer transfer time of the equipments in our fabrication line are measured and compared to the analysis.

Keywords: cluster tool, throughput, FAB, dry etch

NOMENCLATURE

FP = Fundamental Period
ST = Standard Time
P = Process Time
P_{cri} = Critical Process Time
T_1, T_2, T_3, T_4 = Wafer Transfer Time
N = Number of Process Chamber
I_p, I_r= Idle Time of Process Chamber and Robot
U_p, U_r = Utilization of Process Chamber and Robot
U = Utilization of Equipment
α = Price of Process Chamber
β = Price of Equipment except Process Chambers

I. INTRODUCTION

Modern semiconductor manufacturing processes such as dry etching, CVD (Chemical Vapor Deposition), sputtering are conducted by cluster tool type equipments. Fig. 1 is photography of a cluster tool which is consisted of a number of process chambers and loadlock, all accessible through a backbone that houses a robot for transferring wafers. The price for typical cluster tool type equipment is about several million dollars because all the mechanical parts of the cluster tool are fully automated and made for high vacuum and clean environments. So, throughput of cluster tool type equipment - number of wafers which can be processed for an hour - is very important issue for every semiconductor fabrication line (FAB).

The throughput behavior of the cluster tool depends on the relationship between the process time to wafer transfer time ratio. When the ratio is relatively small, the robot is always busy, the chambers are underutilized, and the throughput is a linear function of the wafer transfer time. On the contrary, when the ratio is large, the robot is sometimes idle. The throughput in this case depends on both the process time and the wafer transfer times [1].

Throughput of cluster tool is also influenced by the type of the robot in the equipment's central chamber. Analysis indicates that a dual blade robot improves the throughput of the cluster tool over a single blade robot when the process time to wafer transfer time ratio is relatively small. Under this condition, a cluster tool with a single-blade robot would need to double the speed of the robot, compared with a dual blade robot of equivalent speed, to achieve similar throughput. When the process time to wafer transfer time ratio is relatively large, the throughput of the cluster tool is the same for both dual blade and single blade cluster tools [2]. Loadlock structure also influences the throughput behavior of the cluster tool. So, batch type loadlock or single wafer type loadlock can be selected for a adequate process [3]. Scheduling algorithm of the robot also plays important role to the throughput of the cluster tool. To optimize the scheduling algorithm of the robot, Petri net models of the equipment is used by other researchers [4].

Based on the previous throughput researches for the cluster tool, we analyze and focus on the strategies for maximizing the throughout of the cluster tools in the real FAB. It is common that there are tens of same kinds of cluster tools which are in charge of a single process to meet the required productivity of the FAB. In our FAB, 15 cluster tools are used for a kind of dry etching process. The process time ranged from 40 to 190sec. In this case, it is important issue that one can select adequate process time that maximizes the utilization of the process chambers and the robot. Also, given process time, it needs a rule with which one can select

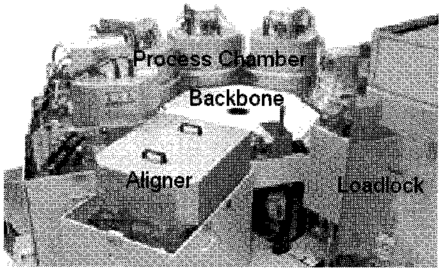

그림 1. 클러스터툴의 사진(ULVAC Technologies Inc.).
Fig. 1. Cluster tool (Photography by ULVAC Technologies Inc.).

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optimal number of process chambers. This can be achieved by maximizing the utilization of the equipment which is the weighted sum of the utilizations of the process chamber s and the robot. Theoretically, the throughput of each cluster tool must be the same but we find that the throughput of the cluster tools vary largely between the equipments. In our FAB, the throughput variation between the equipments reached up to 23%. The throughput variation of the equipment can be analyzed with respect to the variation of wafer transfer time between the cluster tools. It can be proposed that the wafer transfer times of the each equipment must be finely monitored and improved in the real FAB.

II. THROUGHPUT MODELING

Fig. 2 is the schematics of dry etch equipment in our FAB. The dry etch equipment consisted of octagonal backbone and dual blade vacuum robot which has two blades on the opposite side (arm A and arm B). It is also equipped with three process chambers and a wafer aligner. Three-process chambers execute the same processes in a parallel way. Loadlock plays a role of putting wafers into the equipment from the outside (left loadlock) and pulling out the wafers from the inside (right loadlock).

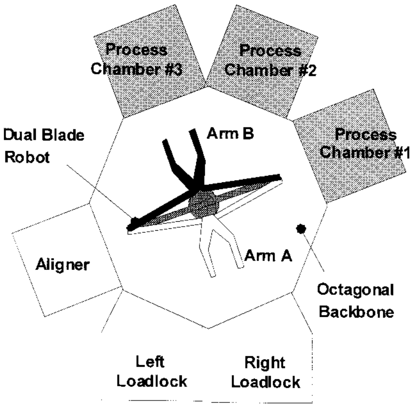


그림 2. 드라이에치 장비의 개략도.

Fig. 2. Schematics of dry etch equipment.

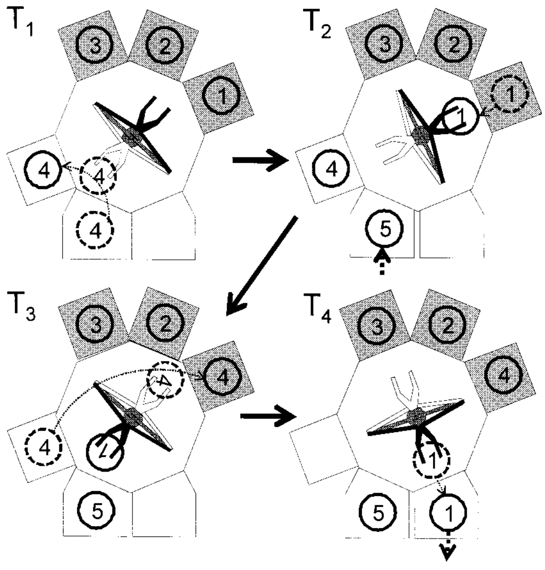
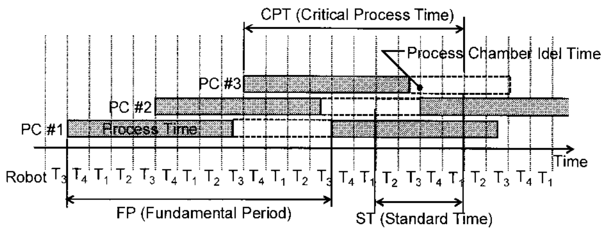
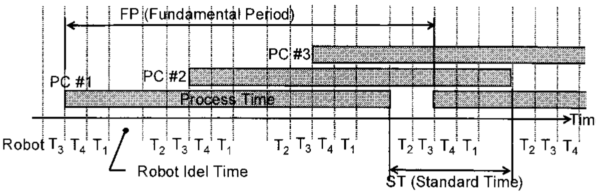


그림 3. 듀얼블레이드 로봇의 웨이퍼 이송 순서.

Fig. 3. Wafer transfer sequences of the dual blade robot.



(a) Case I



(b) Case II

그림 4. 사이클 타임 도표.

Fig. 4. Cycle time chart.

Wafer transfer sequences of a dual blade robot are classified to the 4 distinct steps as represented in fig. 3. The four steps should be completed sequentially to produce a sheet of wafer. At step T_1, arm A of the robot transfers a wafer from the left loadlock to the aligner in which wafer is oriented to a specific direction. At step T_2, arm B of the robot extract the wafer that was processed in the process chamber #1 into the backbone. At the next step T_3, the wafer in the aligner is transferred to the process chamber #1 by arm A of the robot. At the final step T_4, arm B of the robot transfers the wafer which was extracted at step T_2 to the right loadlock. And all the four steps are conducted repeatedly.

To analyze the throughput characteristics of the cluster tool, it is straightforward to make a cycle time chart of it as is pictured at fig. 4. The upper part of the time axis is the sequence of the process chamber and the lower part of it is the sequence of the robot. Fig. 4(a) is the cycle time chart for which the process time is shorter than robot transfer time and fig. 4(b) is for which the process time is longer than robot transfer time.

For both fig. 4(a) and (b), fundamental period of the each process chamber must be equal to the fundamental period of the robot multiplied by the number of the process chambers. ($FP_{process\ chamber} = FP_{robot}$) Fundamental period is defined as the time between subsequent completed steps of process chamber and the robot.

$$P + I_p = N(T_1 + T_2 + T_3 + T_4) \quad \text{(fig. 4.(a))} \tag{1}$$

$$P + T_2 + T_3 = N(T_1 + T_2 + T_3 + T_4 + I_r) \quad \text{(fig. 4.(b))} \tag{2}$$

The left terms of the above equations are the fundamental period of each process chamber and the right terms are the fundamental period of the robot. Process chamber idle time I_p is inevitable because the transferring robot is still busy when the process was finished at fig. 4(a). Robot idle time I_r is also inevitable because wafer is still being processed when the robot is ready to take the wafer out of the process chamber at fig. 4(b).

In case that I_r is zero from the equation (2), we can derive the critical process time, P_{cri} as equation (3). It is important to notice that both the process chamber and the robot are fully utilized when the cluster tool is processing a wafer whose process time is

P_{cri}.

$$P_{cri} = N(T_1 + T_4) + (N-1)(T_2 + T_3) \qquad (3)$$

When process time is shorter than P_{cri}, each process chamber is not fully utilized. In that case, the process chamber idle time I_p can be calculated as equation (4). On the contrary, the robot is not fully utilized when process time is larger than P_{cri}. In that case, the robot idle time I_r can be calculated as equation (5)

$$I_p = \begin{cases} -P + N(T_1 + T_2 + T_3 + T_4) & (P < P_{cri}) \\ T_2 + T_3 & (P > P_{cri}) \end{cases} \qquad (4)$$

$$I_r = \begin{cases} 0 & (P < P_{cri}) \\ \dfrac{P - N(T_1 + T_4) - (N-1)(T_2 + T_3)}{N} & (P > P_{cri}) \end{cases} \qquad (5)$$

The time interval for producing each sheet of wafer in a cluster tool is defined as the standard time (*ST*). It can be derived from equation (1), (2) in which *FP* is divided by the number of process chambers, *N*.

$$ST = \begin{cases} T_1 + T_2 + T_3 + T_4 & (P < P_{cri}) \\ \dfrac{P + T_2 + T_3}{N} & (P > P_{cri}) \end{cases} \qquad (6)$$

Finally, throughput is defined as number of wafers that can be processed for an hour as below.

$$\text{Throughput (wafers/hr)} \equiv \frac{3600}{ST} = \begin{cases} \dfrac{3600}{T_1 + T_2 + T_3 + T_4} & (P < P_{cri}) \\ \dfrac{3600N}{P + T_2 + T_3} & (P > P_{cri}) \end{cases} \qquad (7)$$

III. THROUGHPUT ANALYSIS

1. Utilization of the process chamber and the robot

To clearly understand the throughput behavior of the dry etch equipment, it is desirable to define the utilization. First, utilization of the process chamber can be derived from equation (1) and (4) which is defined by *FP* to I_p ratio.

$$U_p,\ \text{Utiliz. of the process chamber (\%)} \equiv 100\left(1 - \frac{I_p}{FP}\right)$$

$$= \begin{cases} \dfrac{100P}{N(T_1 + T_2 + T_3 + T_4)} & (P < P_{cri}) \\ \dfrac{100P}{P + T_2 + T_3} & (P > P_{cri}) \end{cases} \qquad (8)$$

Second, utilization of the robot can also be derived from equation (2) and (5) which is defined by *FP* to I_r ratio and *N*

$$U_r\ \text{Utiliz. of the robot (\%)} \equiv 100\left(1 - N\frac{I_r}{FP}\right)$$

$$= \begin{cases} 100 & (P < P_{cri}) \\ \dfrac{100N(T_1 + T_2 + T_3 + T_4)}{P + T_2 + T_3} & (P > P_{cri}) \end{cases} \qquad (9)$$

Fig. 5 shows the diagram for process time versus throughput and utilization for the dry etch equipment. Table 1 is wafer transferring time of the dry etch equipment in our FAB. Wafer transfer time is determined by the speed of the robot, open and close time of a slit door between chambers and vacuum stabilization time, etc.

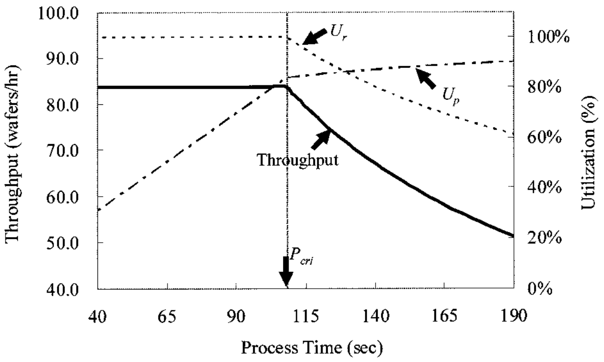


그림 5. 생산성 및 이용도.

Fig. 5. Throughput and utilization.

표 1. 드라이에칭 장비의 웨이퍼 이송 시간.

Table 1. Wafer transfer times for the dry etch equipment in the FAB.

T_1	T_2	T_3	T_4
18 sec	13 sec	8 sec	4 sec

The throughput of the dry etch equipment increases with decreasing process time, and this region is called the process-bound condition. On the other hand, the region wherein the throughput stops increasing and plateaus is called the transfer-bound condition. The corresponding process time is called the critical process time, P_{cri}. The critical process time of the dry etch equipment can be computed using equation (3), which is 108 sec for the values of table 1. Fig. 5 and equation (7) shows that if the process time is shorter than P_{cri}, the throughput of the dry etch equipment is independent of the process time; instead, it is determined by T_1, T_2, T_3, and T_4. On the other hand, if the process time is longer than Pcri, the throughput is determined by process time and T_2, T_3. It is independent of T_1 and T_4, however.

From the view of economics, the utilization of the equipment must be maximized. Utilization of the process chamber increases linearly with increasing process time but the slope of the curve slows down over the critical process time. Utilization of the robot is 100% below P_{cri} and decreases to 0% asymptotically over the P_{cri}. From the fig. 5, it is reasonable that the equipment be allotted to the process whose processing time is near the P_{cri}. When it is allotted to the process whose processing time is shorter than P_{cri}, the utilization of the process chamber decreases severely and consequently the equipment is used wastefully. It is also wasteful to use the equipment beyond the P_{cri} because utilization of the robot drops sharply but the utilization of the process chamber increases slightly.

2. Otimal number of process chambers

A cluster tool must be equipped with optimal number of process chambers that maximizes the equipment utilization. The equipment utilization may be defined as weighted sum of the utilization of the process chambers and the robot. It is reasonable that the price of the process chamber and the robot be selected as the weighting values. So, the equipment utilization is defined as equation (10). Here, α means the price of a single process chamber and β means the price of the equipment except the process chambers. Of course, β includes the price of the robot which is in the central chamber.

$$U \equiv \frac{N\alpha U_p + \beta U_r}{N\alpha + \beta} = \begin{cases} \dfrac{100}{N\alpha+\beta}\left(\beta + \dfrac{\alpha P}{T_1+T_2+T_3+T_4}\right) & (P < P_{cri}) \\ \dfrac{100N}{N\alpha+\beta}\left(\alpha + \dfrac{\beta(T_1+T_4)+(\beta-\alpha)(T_2+T_3)}{P+T_2+T_3}\right) & (P > P_{cri}) \end{cases} \qquad (10)$$

With equation (10), optimal problem can be expressed as below.

Optimal Problem: given P, select N that maximizes U

The optimal problem can be solved by observing the characteristics of the equation (10). The upper part of equation (10) is increasing function with process time, P. And the lower part of it is decreasing function with P because the β is typically larger than α. For the dry etch equipment in our FAB, the value of β is about five hundred thousand dollars and the value of α is about one million dollars. So, the maximum condition of U occurs when $P = P_{cri}$. This condition can be converted with respect to N using equation (3). Finally, the optimal solution can be described as equation (11)

Fig. 6 is the diagram of equation (11), which is stepwise increasing function with respect to P because of integer nature of the N. With fig. 6, engineers can select optimal number of process chambers given P. Important conclusion about the structure of semiconductor equipment can be derived from fig. 6. For relatively long time process, it is desirable to attach many process chambers to a single robot. In this case, cluster tool structure is adequate because the structure was originally designed to be able to attach many chambers to a single robot. But cluster tool structure is not adequate for relatively short time process.

$$N_{optimal} = \frac{P+T_2+T_3}{T_1+T_2+T_2+T_4} \qquad (11)$$

In that case, necessary number of process chambers is only one or two considering the equipment's utilization of fig. 6. So, it is better to adopt a single process chamber plus a single robot structure than multi process chamber plus a single robot structure, namely cluster tool.

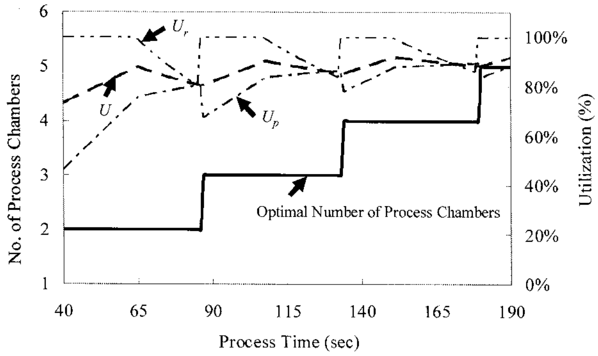


그림 6. 공정 체임버의 최적 개수.

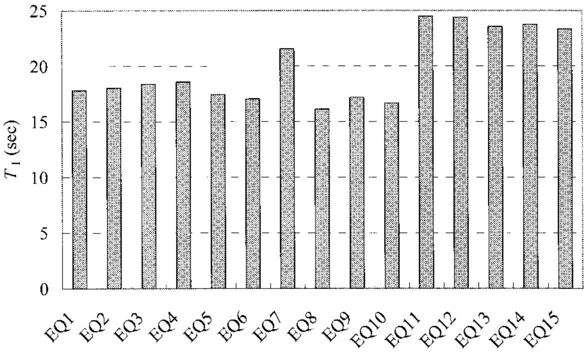
Fig. 6. Optimal number of process chambers.

3. Throughput variation due to wafer transfer time variation

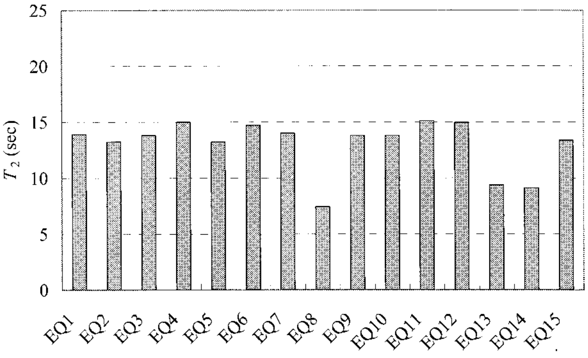
The values of table 1 are the wafer transfer times of the dry etch equipment in our FAB, which was originally designed by the equipment manufacturer. Ideally, the wafer transfer times of the same kind of equipments in the FAB should be equal to the values of table 1. But the realities of the FAB are very different from that. Fig. 7 shows the wafer transfer times T_1 and T_2 which were measured for 15 equipments in our FAB. All the 15 equipments are equipped with 3 process chambers and their wafer transfer times were originally setup to have the same values of table 1. But fig. 7 shows that the maximum variation of T_1 given an average of 20.0sec between pieces of equipment is 23%. Likewise, the maximum variation of T_2 given an average of 13.0sec is 43%.

A wafer transfer time is composed of many detailed sub steps. For example, step T_1 is composed of vacuum pumping/venting, slit valve open/close, robot translation/rotation etc. For each equipment, it is necessary to tune finely the sub steps for the purpose of reducing the particle generation, vacuum haunting, wafer scratching etc. As the result of such tuning, the wafer transfer times of 15 equipments vary as fig. 7.

The throughput variation of fig. 8 can be understood by equation (7). Fig. 9 is the throughput curves when the wafer



(a) Wafer transfer time, T1



(b) Wafer transfer time, T2

그림 7. 웨이퍼 이송 시간의 측정 결과.

Fig. 7. Measurements of wafer transfer times.

표 2. 웨이퍼 이송 시간 분포.

Table 2. Wafer transfer time variation.

Wafer transfer time	Ave. (sec)	Range (sec)	Variation (%)
T1	20.0	8.4	23%
T2	13.0	7.7	43%

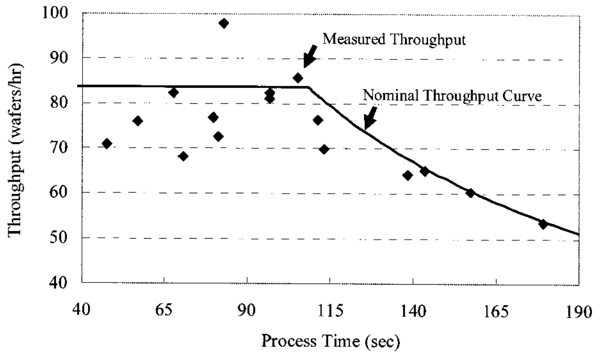


그림 8. 생산성 측정 결과.

Fig. 8. Measurements of throughput.

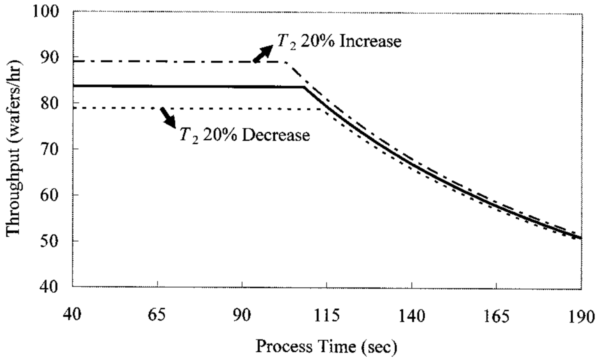


그림 9. 웨이퍼 이송 시간 변동에 따른 생산성 변동.

Fig. 9. Throughput variation due to wafer transfer time variation.

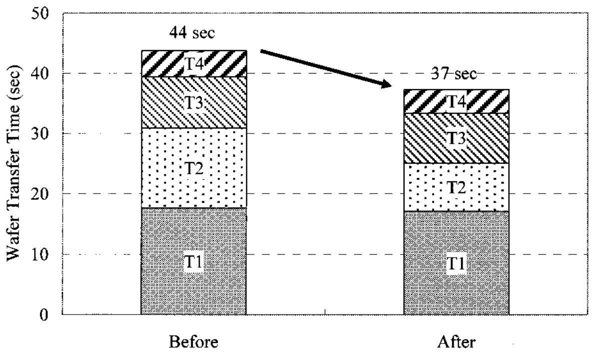


그림 10. 웨이퍼 이송 시간 개선(5호기).

Fig. 10. Improvements of wafer transfer time (EQ5).

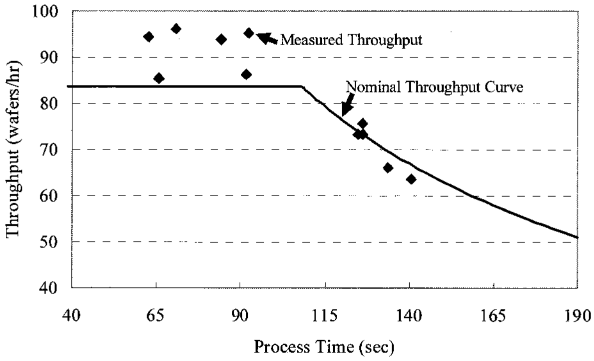


그림 11. 웨이퍼 이송 시간 개선 후 생산성 측정 결과.

Fig. 11. Measurements of throughput after wafer transfer time improvements.

transfer time T_2 varies 20% from values of table 1. When the process time is less than P_{cri}, the throughput variation is 6%. On the contrary the throughput variation is negligible when the process time is larger than P_{cri}. The throughput trend of fig. 7 corresponds with measured throughput of fig. 8.

Due to the wafer transfer time variation, throughput of the each equipment also varies. For our FAB, 15 pieces of equipment are used for a single dry etch process of a specific film. The process time ranges from 40sec to 190sec. Fig. 8 presents the result of measured process time and throughput for the pieces of equipment. Given an average throughput of 79wafers/hr, the throughput differences between pieces of equipment are measured at a maximum of 23% if process time is less than critical process time, 108sec. On the other hand, given a process time of more than 108sec, throughput variation is negligible.

The wafer transfer time variation should be minimized to reduce the throughput variation between pieces of equipment. In our FAB, the wafer transfer times have been modified by changing the several parameters in each piece of equipment. For example, though the speed of the robot can not be increased because of the slippage between the wafer and robot blade, the speed of the robot without wafer can be easily increased. The speed of slit door open/close also can be increased so far as it does not generate particles within the process chambers. Fig. 10 presents the wafer transfer times of EQ5 before and after the modifications. For EQ5, the speed of robot without wafer which is a sub step of the T_2 was increased 40% and total transfer time was reduced from 44sec to 37sec. Fig. 11 shows the diagram for process time versus throughput after the modifications for all the 15 equipments. Improvements are done mainly in the region where the process time is less than critical process time.

Given a process time of less than 108sec, the average throughput is increased from 79wafers/hr to 92wafers/hr and the maximum throughput variation decreased from 23% to 7%. From above measurements and analysis, we propose that the wafer transfer times of the each equipment must be finely monitored and improved in the real FAB, especially for the process whose processing time is less than equipment's critical process time.

IV. CONCLUSION

In this research, we analyzed and focused on the strategies for maximizing the throughout of cluster tools in the real FAB. For that purpose, throughput of dry etch equipment which has 3 process chambers and a single dual blade robot was modeled using equipment's cycle time chart. Three topics about the throughput were analyzed. First, utilization of the process chamber and the robot were defined and analyzed for the dry etch equipment in our FAB. It is recommended that a cluster tool be allotted to the process whose processing time is near the equipment's critical process time. Second, to fully utilize the dry etch equipment, it is necessary that adequate number of process chambers be equipped to the backbone. Especially, it is desirable to adopt a single process chamber plus a single robot scheme for short time process and multi process chambers plus a single robot scheme for long time process. Finally, the throughput variation was analyzed using a throughput model and measured for 15 equipments in our FAB. To minimize the throughout variation, it is necessary that engineers finely monitor and improve the wafer transfer time of each cluster tool, especially for the process whose processing time is relatively short.

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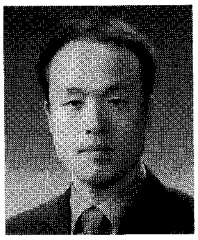

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