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Giga-fab Scale Determination Model for Wafer Fabrication Based on Production Performances

Ying-Mei Tu and Che-Hao Chang

Abstract—**In order to meet market demand and enhance the competitive advantage, the semiconductor manufacturing companies have to expand the capacity in the existed fab or build up new fabs. Normally, there are two characteristics of new fab: more advanced technology and larger scale than existed fab. Moreover, there will have several production phases associated with automatic material handling system in a fab and it is called as a giga-fab. As everyone knows, there are many benefits of giga-fab, such as lower cost, shorter cycle time and more flexibilities…,etc. Accordingly, the production scale of giga-fab is larger than before so as to get more benefits. Nevertheless, the optimal scale of giga-fab is still an issue in this decade.**

In this work, a model to determine the scale of a giga-fab is proposed. Production performance is the major factor to determine the scale of fab in this model. Based on the results of previous simulation experiments, they revealed that the fab scale will only improve the production cycle time significantly. Therefore, the GI/G/m queuing model is applied to build up the queue time equations of bottleneck machine. In order to find out the numbers of bottleneck machine under the minimum queue time, the differentiation is used on its expected waiting time equation. Accordingly to the calculation result, the best numbers of bottleneck machines can be decided. That means the optimal fab scale under minimum cycle time is also determined.

***Index Terms*—Giga-fab, Production performance, Queuing model, Semiconductor fabrication**

I. INTRODUCTION

RECENTLY, in order to meet market demand and enhance the competitive advantage, the semiconductor manufacturers intend to build up a huge fab to fulfill the requirements. The main purpose is to allow the fabs towards the so-called economies of scale. The concept of giga-fab is occurred under this situation. However, there is no any unified norm and recognition for the giga-fab. It usually refers to a fab with monthly production capacity of 100,000 wafers or more, and plant building is not confined to a single area or a single building. Therefore, most of the so-called giga-fabs are composed of many phases connected by Automatic Material Handling System (AMHS). Although the advantages of giga-fab are well known, there still has no any perfect theoretical basis for setting the best scale of a giga-fab.

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Generally, large scale of fab will be easier to reach the economy of scale to reduce the manufacturing costs, shorten production cycle time, improve delivery accuracy and flexibility. Nevertheless, the expandability of production capacity is not infinite since the huge fab scale will increase the risks not only on production management, but also on demand fluctuation and accident occurrence.

Regarding to the topic of fab scale, capacity planning is the key issue to be addressed. In the previous studies of capacity planning, the most important factor is the uncertainty of market demand. Therefore, most of literatures adopted linear programming or stochastic integer programming model and assumed future demand trend as several demand scenario models with different occurrence probabilities to calculate optimal strategy [[3]. Cakanyıldırım and Roundy [2] used Polynomial time Expansion Algorithm to propose a set of methods for solving planning problems of plant construction under uncertain demand. Simulation system is another constantly used method in highly uncertain demand environment [5]][6]. The advantage of this method is that uncertainty factors of environmental demands can be defined by the stochastic behaviors of simulation. Besides, the methodology of decision analysis was also applied to the capacity planning. Chien *et al.* [1] proposed a model using mini–max regret strategy for capacity planning under demand uncertainty to improve capacity utilization and capital effectiveness in semiconductor manufacturing.

In addition, there were some researches to study the effect of production performance of fab scale. Benavides *et al.* [1] proposed an estimation model for calculating out better plant scale and planning method under demand uncertainty environment. The result revealed that the bigger fab scale, the more gains and benefits it can reach, and the easier it can achieve economies of scale; unfortunately, the environment considered in this study is a 200mm fab with monthly production capacity of 20K. Rose [6] used a simulation approach to explore the economic effect of giga-fab. The result showed that, when fab scale getting bigger, its production cycle time will be improved. However, the environmental conditions of the experiment were too simple in this study. It did not carry out further investigations on other potential factors.

In this work, the first task is to simplify the equations of expected waiting time in GI/G/m queuing model. Accordingly, a simulation model is developed to survey and analyze the effect of fab scale on the squared coefficient of variation of arrival rate (C_a^2) of the workstation and the squared coefficient of variation of service time (C_s^2) of the workstation. Based on the finding from simulation experiments, a queuing model to represent the relationship

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between the expected waiting time of products and numbers of machine is developed. In order to look for the best fab scale, the differential equations are applied to evaluate the numbers of machine under minimum waiting time.

II. Simulation Experiment

A. *Simulation Environment*

Simulation experiment is constructed to find the relationship between some independent factors (product mix complexity and fab scale) and two parameters of queuing system, C_a^2 and C_s^2. Generally, fabs can be divided into two types, integrated device manufacturer (IDM) and foundry house. An IDM mainly produces its own products, so the categories of its products are usually not many, i.e., low product mix complexity. Oppositely, a foundry house mainly produces products commissioned by customers, so its product mix complexity is relatively high. Therefore, the product mix complexity was used to distinguish the two mainstreams of fabs in the experiment of this study.

With regards to the settings of fab scale, this study mainly investigated the effect of constant scale expansion on C_a^2 and C_s^2 trend. It used different release rate to carry out the settings of production scale. Besides, the basis machine utilization rate is applied to adjust the numbers of machine. As for the levels of production scale factor, this study used 10K as unit to conduct related settings of levels (50K to 100K).

B. *Experimental Result Analysis*

Due to lithograph module is usually the bottleneck of wafer fabrication, all analyses of experimental result only focus on this workstation. Table 1 is the mean value of C_a^2 and C_s^2 from simulation experiment and Fig. 1 is the trend chart. From Fig. 1, it shows the trends of C_a^2 and C_s^2 by fab scale. In order to make sure that C_a^2 and C_s^2 will not change by fab scale, the statistical *t*-test analysis is applied. The t-test results are shown as Table 2~5. Based on these results, all *p*-values at 95% confidence level are bigger than 0.05, it reveals that there are no significant differences between all C_a^2 and C_s^2. Therefore, no matter low or high product mix complexity, C_a^2 and C_s^2 are all independent with fab scale.

Table 1
The mean value of C_a^2 and C_s^2 from simulation experiment

	50K	60K	70K	80K	90K	100K
Ca^2_Low	1.0179	1.0192	1.0172	1.0167	1.0158	1.0155
Cs^2_Low	0.7433	0.7453	0.7463	0.7447	0.7442	0.7455
Ca^2_High	1.0503	1.0509	1.0482	1.0462	1.0451	1.0452
Cs^2_High	0.7901	0.7903	0.7946	0.7902	0.7937	0.7960

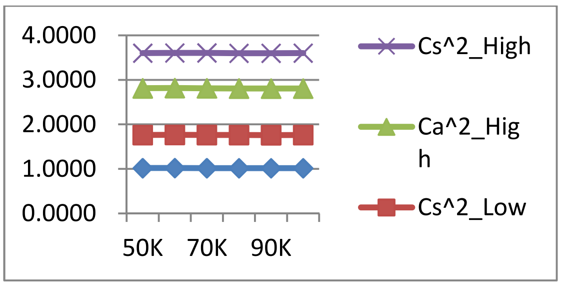

Fig. 1 : The trend of C_a^2 and C_s^2

Table 2
ANOVA
Photo_C_a^2 under high product mix complexity

	Sum of squares	df	Mean square	F	Sig.
Between Group	.000	5	.000	.190	.966
Within Group	.023	114	.000		
Total	.023	119			

Table 3
ANOVA
Photo_C_s^2 under high product mix complexity

	Sum of squares	df	Mean square	F	Sig.
Between Group	.001	5	.000	1.592	.168
Within Group	.009	114	.000		
Total	.010	119			

Table 4
ANOVA
Photo_C_s^2 under low product mix complexity

	Sum of squares	df	Mean square	F	Sig.
Between Group	.000	5	.000	.190	.966
Within Group	.023	114	.000		
Total	.023	119			

Table 5
ANOVA
Photo_C_s^2 under low product mix complexity

	Sum of squares	df	Mean square	F	Sig.
Between Group	.000	5	.000	.268	.930
Within Group	.013	114	.000		
Total	.013	119			

III. Fab Scale Determination Model

Based on the previous studies [6], [7], they revealed that the fab scale will have significant influences on the mean production cycle time and its deviation only. Therefore, production cycle time is the key factor to determine the fab scale when the scale design focuses on production performance. Besides, as everyone knows that factory output is limited by its bottleneck machine [8]. That means factory capacity is determined by bottleneck machine. Therefore, the

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GI/G/m queuing model is applied on the bottleneck machine to determine the fab scale. Generally, lithograph module is the bottleneck of wafer fabrication because of heavy capital investment and low throughput. Under this situation, the study can only focus on lithograph module to build up the determination model.

A. Notation

The following data were required for the waiting time model .

λ_j arrival rate of workstation *j*

τ_j mean service time of workstation *j*

C_{sj}^2 the SCV of service time of workstation *j*

m_j total number of machine at a workstation *j*

ρ_j utilization of workstation *j*

B. Waiting Time Model

In order to study the behavior of lithograph module, a queuing system can be established. In this system, the production cycle time includes two segments, processing time and queue time. Processing time is more specific and hard to change in general. Queue time is the time period that parts wait to be processed in the queue. It is more uncertain than processing time and always be fluctuated by the environment. Therefore, in order to minimize the cycle time, queue time is the major element to be studied.

The system is modeled as a GI/G/m queue that has m identical machines, a first-in-first-served queue, and inter-arrival and service time are derived from independent identically distributed (iid) random variables with general distributions.

The waiting time estimation applied in this work is developed by Whitt [9]. According to this approximation, expected waiting time can be determined by the following different cases.

Case I:

When $C_{aj}^2 \geqq C_{sj}^2$ and C≧1 ($\frac{c_{aj}^2+c_{sj}^2}{2} = C$)

$$EW_j = \left[\left(\frac{4(c_{aj}^2-c_{sj}^2)}{4c_{aj}^2-3c_{sj}^2}\right)\times\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right) + \left(\frac{c_{sj}^2}{4c_{aj}^2-3c_{sj}^2}\right) \right] \times\frac{c_{aj}^2+c_{sj}^2}{2}\times\frac{\tau_j(\rho_j^{\sqrt{2(m_j+1)}-1})}{m_j(1-\rho_j)} \quad (1)$$

Case II:

When $C_{aj}^2 \geqq C_{sj}^2$ and 0≦C<1 ($\frac{c_{aj}^2+c_{sj}^2}{2} = C$)

$$EW_j = \left[\begin{array}{l} \left(\frac{4(c_{aj}^2-c_{sj}^2)}{4c_{aj}^2-3c_{sj}^2}\right)\times\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right)+\left(\frac{c_{sj}^2}{4c_{aj}^2-3c_{sj}^2}\right)\times \\ \left[\frac{\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right)}{2} + \frac{\left(1-4\times\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right)\right)\exp(-2(1-\rho_j)/3\rho_j)}{2} \right]^{2(1-C)} \end{array} \right] \times\frac{C_{aj}^2+C_{sj}^2}{2}\times\frac{\tau_j(\rho_j^{\sqrt{2(m_j+1)}-1})}{m_j(1-\rho_j)} \quad (2)$$

Case III:

When $C_{aj}^2 < C_{sj}^2$ and C≧1 ($\frac{c_{aj}^2+c_{sj}^2}{2} = C$)

$$EW_j = \left[\left(\frac{(c_{sj}^2-c_{aj}^2)}{2c_{aj}^2+2c_{sj}^2}\right)\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right) + \left(\frac{c_{sj}^2+3c_{aj}^2}{2c_{aj}^2+2c_{sj}^2}\right) \right] \times\frac{(c_{sj}^2+c_{aj}^2)}{2}\times\frac{\tau_j(\rho_j^{\sqrt{2(m_j+1)}-1})}{m_j(1-\rho_j)} \quad (3)$$

Case IV:

When $C_{aj}^2 < C_{sj}^2$ and 0≦C<1 ($\frac{c_{aj}^2+c_{sj}^2}{2} = C$)

$$EW_j = \left[\begin{array}{l} \left(\frac{(c_{aj}^2-c_{sj}^2)}{2c_{aj}^2-2c_{sj}^2}\right)\times\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right)+\left(\frac{c_{sj}^2+3c_{aj}^2}{2c_{aj}^2-2c_{sj}^2}\right)\times \\ \left[\frac{\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right)}{2} + \frac{\left(1-4\times\left(1+\frac{(1-\rho_j)(m_j-1)(\sqrt{4+5m_j}-2)}{16m_j\rho_j}\right)\right)\exp(-2(1-\rho_j)/3\rho_j)}{2} \right]^{2(1-C)} \end{array} \right] \times\frac{C_{aj}^2+C_{sj}^2}{2}\times\frac{\tau_j\times(\rho_j^{\sqrt{2(m_j+1)}-1})}{m_j(1-\rho_j)} \quad (4)$$

B. Let EW be the function of m

In order to get the relationship between system scale and expected waiting time, the above equations should be distinguished *m* (numbers of machine) dependent variables from *m* independent variables and replace all *m* dependent variables with *m*. Finally, the equations EW_j will be the functions of *m*. Appling differential to EW_j, the Inflection points can be solved. After reviewing all inflection points, the *m* which can reach the minimum EW_j can be evaluated.

Although the concept of the determination model is easy to realize, the equations of EW_j are too complicated to apply the differential. Based on the result of previous simulation experiments, it revealed that the influence of fab scale change on C_a^2 and C_s^2 are slight. Besides, the values of C_a^2

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and C_s^2 are small. Under this situation, we can assume that these two variables to be the *m* independent variable. Based on this assumption, the equations of *EW(m)* can be simplified. Regarding to the mean service time (τ_j) and machine utilization (ρ_j), they still can be regarded as the *m* independent variable. Generally, no matter how big the fab scale, the mean service time will keep the same under the same product mix. Besides, we usually assume the equipment utilization keeping the same under the expansion of fab. The simplified *EW(m)* are showed as follows.

Case I :

$$EW_j = \left[A \times \left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j m_j} \right) + D \right] \times C \times \frac{\tau_j (\rho_j^{\sqrt{2(m_j+1)}-1})}{B \times m_j} \tag{5}$$

$$A = \frac{4\left(C_{aj}^2 - C_{sj}^2\right)}{4C_{aj}^2 - 3C_{sj}^2} \tag{6}$$

$$B = (1 - \rho_j) \tag{7}$$

$$C = \frac{c_{aj}^2 + c_{sj}^2}{2} \tag{8}$$

$$D = \frac{C_{sj}^2}{4C_{aj}^2 - 3C_{sj}^2} \tag{9}$$

Case III :

$$EW_j = \left[A' \times \left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j m_j} \right) + D' \right] \times C \times \frac{\tau_j (\rho_j^{\sqrt{2(m_j+1)}-1})}{B \times m_j} \tag{10}$$

$$A' = \frac{c_{sj}^2 - c_{aj}^2}{2c_{aj}^2 + 2c_{sj}^2} \tag{11}$$

$$D' = \frac{c_{sj}^2 + 3c_{aj}^2}{2c_{aj}^2 + 2c_{sj}^2} \tag{12}$$

Case II :

$$EW_j = \left[A \times \left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j \times m_j} \right) + D \times \left[\frac{\left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j \times m_j} \right)}{2} + \frac{\left(1 - 4 \times \left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j \times m_j} \right) \right) \exp(E)}{2} \right]^{-2(1-C)} \right] \times C \times \frac{\tau_j (\rho_j^{\sqrt{2(m_j+1)}-1})}{B \times m_j} \tag{13}$$

$$E = -2(1 - \rho_j)/3\rho_j \tag{14}$$

Case IV :

$$EW_j = \left[A' \times \left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j \times m_j} \right) + D' \times \left[\frac{\left(1 + \frac{(1-\rho_j)(m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j \times m_j} \right)}{2} + \frac{\left(1 - 4 \times \left(1 + \frac{B \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j \times m_j} \right) \right) \exp(E_j)}{2} \right]^{-2(1-C)} \right] \times C \times \frac{\tau_j \times (\rho_j^{\sqrt{2(m_j+1)}-1})}{B \times m_j} \tag{15}$$

C. Differential EW by m

In this step, in order to get the inflection points, *EW* functions in four cases have to execute the first order differential by *m*. From the differential result, there are only two different first order differential equations existed. The first order differential equations are shown as follows.

Case I & III :

$$\frac{dEW_j}{dm_j} = (A + D) \times \left[C \times \tau_j \times \left(\frac{\left(\rho_j^{\sqrt{2(m_j+1)}-1} \times \ln \rho_j \times \frac{1}{\sqrt{2(m_j+1)}} \right)}{(B \times m_j)} - \frac{(B \times \rho_j^{\sqrt{2(m_j+1)}-1}}{(B \times m_j)^2} \right) \right] + \left[\frac{A \times B \times C \times \left[\sqrt{4+5m_j} + \frac{5}{2} \times (m_j - 1) \times \frac{1}{\sqrt{4+5m_j}} - 2 \right]}{(16 \times \rho_j \times m_j)^2} - \frac{16 \times \rho_j \times A \times B \times C \times \left(B \times (m_j - 1)(\sqrt{4+5m_j} - 2) \right)}{16 \times \rho_j \times m_j)^2} \right] \times \left[\frac{\tau_j (\rho_j^{\sqrt{2(m_j+1)}-1})}{B \times m_j} \right] + \tau_j \times \left[\frac{A \times B \times C \times (m_j - 1)(\sqrt{4+5m_j} - 2)}{16\rho_j m_j} \right] \times \left[\frac{(B \times m_j) \times \left(\rho_j^{\sqrt{2(m_j+1)}-1} \times \ln \rho_j \times \frac{1}{\sqrt{2(m_j+1)}} \right) - B \times \rho_j^{\sqrt{2(m_j+1)}-1}}{(B \times m_j)^2} \right] \tag{16}$$

Case II & IV :

$$
\begin{aligned}
&\frac{dEW_j}{dm_j} = C\times\frac{\tau_j(\rho_j^{\sqrt{2(m_j+1)}-1})}{B\times m_j}\times \Bigg\{ \frac{A\times B}{16\rho_j}\times\left(\frac{\frac{15}{2}m_j+4-2\sqrt{4+5m_j}}{\sqrt{4+5m_j}\times(m_j)^2}\right)+D\times \\
&(2-2C)\times\Bigg[\Bigg(\frac{1}{2}\left(1+\frac{B\times(m_j-1)(\sqrt{4+5m}_j-2)}{16\rho_j\times m_j}\right)+ \\
&\frac{1}{2}\left(1-4\times\left(1+\frac{B\times(m_j-1)(\sqrt{4+5m}_j-2)}{16\rho_j\times m_j}\right)\right)\exp(E)\Bigg)^{(1-2C)}\times \\
&\Bigg(\frac{B}{32\rho_j}\times\left(\frac{\frac{15}{2}m_j+4-2\sqrt{4+5m_j}}{\sqrt{4+5m_j}\times(m_j)^2}\right)+ \\
&\exp(E)\times\frac{1}{2}\left(-\frac{B}{4\rho_j}\times\left(\frac{\frac{15}{2}m_j+4-2\sqrt{4+5m_j}}{\sqrt{4+5m_j}\times(m_j)^2}\right)\right)\Bigg)\Bigg]\Bigg\}+ \\
&\frac{C\times\tau_j}{B}\times\frac{\left(\left(\ln\rho_j\times\rho_j^{\sqrt{2(m_j+1)}-1}\times\frac{1}{\sqrt{2(m_j+1)}}\right)\times m_j-\rho_j^{\sqrt{2(m_j+1)}-1}\right)}{(m_j)^2}\times \\
&\Bigg[A\times\left(1+\frac{B\times(m_j-1)(\sqrt{4+5m_j}-2)}{16\rho_j\times m_j}\right)+D\times \\
&\Bigg(\frac{\left(1+\frac{B\times(m_j-1)(\sqrt{4+5m}_j-2)}{16\rho_j\times m_j}\right)}{2}+ \\
&\frac{\left(1-4\times\left(1+\frac{B\times(m_j-1)(\sqrt{4+5m}_j-2)}{16\rho_j\times m_j}\right)\right)\exp(E)}{2}\Bigg)^{2(1-C)}\Bigg]
\end{aligned}
\tag{17}
$$

D. *Get and evaluate the inflection points*

In order to get the inflection points of function *EW*, the first order differential equation should be equal to zero. The mathematics software MatLab is applied to solve the differential equations. Generally, there are more than one solutions existed. Therefore, all inflection points should be carried to the original *EW* equation to evaluate and select the one which minimizes the value of *EW*. The '*m'* represents the best numbers of machine in lithography module under minimum cycle time. Because it is the bottleneck of fab, it also represents the best scale of fab.

IV. CONCLUSIONS

In this work, a fab scale determination model is established to decide the best scale of fab based on the production performances. Although the production performance is not the only factor to decide the fab scale, it is really one of the most important factors for semiconductor industry. Under the consideration of production performance, GI/G/m queuing model is applied to decide the fab scale. In order to simplify the equation of expected waiting time, a simulation experiment is used to study the relationship between the fab scale and the queuing parameters, C_a^2 and C_s^2. Finally, the first order differential equation is applied to get the best scale under the minimum cycle time.

Regarding to the future works, the other factors which will influence the fab scale design, such as manufacturing cost, demand fluctuation, accident risk can be taken into account in the determination model.

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