行政院國家科學委員會專題研究計畫年度報告

集結式加工機台之遠端診斷系統

(Remote Control System for a Semiconductor Cluster Tool)

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一、中文摘要

最近幾年來，半導體製造在世界上蓬勃發展，晶圓的尺寸從八吋到變成十二吋，使得單一晶圓製造越來越受重視。集結式機台乃針對單一晶圓製造而開發，其模組可以分為晶圓移載模組（Transfer Module），程序模組（Process Module）及卡匣式晶圓進出模組（Cassette Module）。由於集結式機台是處於晶圓製造廠的無塵室內，工程人員於操作機台時需身著悶熱的防塵衣，造成操作上的不便。若能將監控地點改在一般的環境，工程人員可以免於悶熱，而且可以在任何一台電腦上作監控。本計畫針對集結式機台提出遠端診斷（Remote Diagnosis）及預防保養之系統架構及程式開發。首先將此系統分成四個大狀態集（State Set）：正常操作（Normal Operation）狀態集、效能衰減（Degradation）狀態集、系統故障（Failure）狀態集、保養（Maintenance）狀態集。並且在這些狀態集下將集結式機台的所有狀態表示出來，經由事件驅動（Event Driven）的方式，由狀態之改變，來決定事件的產生。系統分成三層式架構，藉由第一層的偵測及第二層的診斷，維護工程師可以於第三層的遠端瀏覽器監視集結式機台的效能及故障情形。並經由診斷的情形，選擇較佳的解決方式，作為線上修復的依據，或是通知相關人員的參考。

關鍵詞：遠端控制、集結式機台、派區網路、統計製程控制、預防保養

Abstract

In recent years, the manufacturing industry of semiconductor is prosperous in the world. The size of wafer enlarges from 200 mm to 300 mm, and a single wafer processing is getting more and more important. The cluster tool is developed for the purpose of single wafer processing. It consists of transfer module, process module, and cassette module. Since the setup and operation of the cluster tool are always done in the clean room of the IC foundry, the engineers have to suffer from hot and windless dust-proof dress. If the status of the cluster tool can be monitored remotely, it will be very useful for maintenance and diagnosis. In addition, the engineer does not need to wear the dust-proof dress to monitor the tool.

In this project, the system architecture and development for remote diagnosis and preventive maintenance of cluster tools will be proposed. Firstly, we divide the system into four state sets: normal operation state set, degradation state set, failure state set, and maintenance state set. These state sets consist of many states of cluster tools. We can determine the latest events from the former state to the latest state. There are three tiers in this system architecture. By the detection of the first tire and the diagnosis of the second tier, maintenance engineer can monitor the efficiency and failure of cluster tools by remote browser of the third tier.

Keywords: Remote Control, Cluster Tool, Petri net, SPC, Preventive Maintenance

二、計畫緣由及目的

The cluster tool shown in Fig. 1 provides an important technical breakthrough for wafer processing in last decade. It has been widely used in IC fabrication industry. By transferring wafers between process steps through a vacuum load-lock, the cluster tool significantly reduces contamination as compared to other systems, such as furnace, that allow exposure to air during transfer. Therefore, the cluster tool technology becomes more pervasive for highly integrated process applications, such as rapid thermal oxidation, rapid CVD, and clean sequences. In particular, the cluster tool will play an important role in the manufacturing of 300mm wafers.

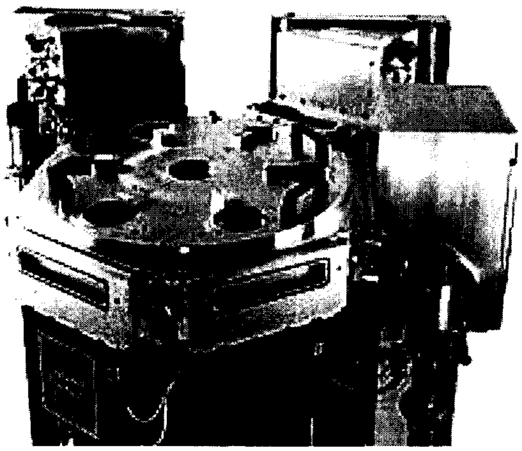

Fig. 1 Cluster tool platform and process modules

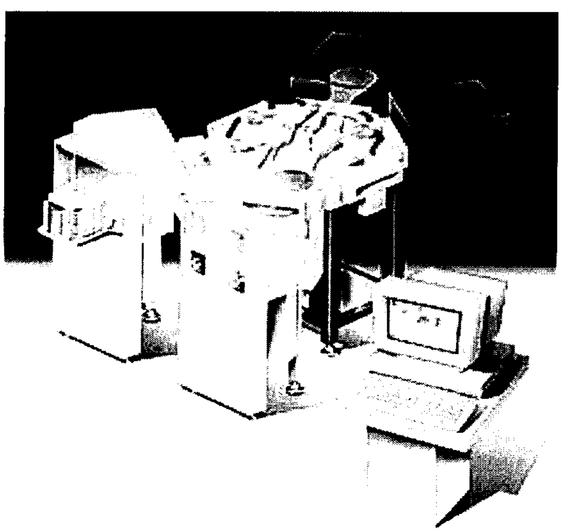

Fig. 2 Cluster tool architecture and its robot module

A cluster tool is an integrated and environmentally isolated wafer manufacturing system. It consists of processing chambers, internal robots to transport wafers, and load locks where the wafer-to-cassette exchange takes place, as shown in Fig. 2. The wafers inside a cassette module are loaded into the cluster tool from the load lock. Each wafer undergoes a number of sequential process steps before leaving the cluster tool. Each process step can be etching, cleaning, oxidation, ion implantation, and so forth.

Equipment reliability and maintenance drastically affect the three key elements of competitiveness: quality, cost and product lead-time. Well-maintained machines can maintain better tolerance, reduce scrap and rework, and raise consistency and quality of the wafer. In a high-performance system, one often cannot tolerate significant degradation in performance during normal system operation. If the behavior of a machine can be monitored adaptively, then an early warning of possible faults can be generated. The development of in-process monitoring of machine degradation and faults is one of the most important research tasks for increasing machine uptime and improving production quality.

Since Internet is developed prosperously, the trend of remote control through Internet makes the idea of remote diagnosis. When the operation environment is hazardous or tough, the operators can control machines at a remote and comfortable situation. Since the cluster tool is placed inside the clean room, the engineer who operate cluster tools should wear dust-proof dress which makes human hot and windless. If we could control and diagnose cluster tools from any computer outside the clean room, the comfortable environment should make operators more efficient and concentrate. The research on remote diagnosis of cluster tools is seldom addressed although there are many researches on remote diagnosis of other fields.

Generally speaking, the operational performance of components, machines, and process can be divided into four states [4]: the normal operation state; the degraded state; maintenance state; and the failure state.

The degraded states can be defined at a gross level or at a detailed level. At a gross level, a component is described as degraded whenever corrective maintenance is required, such as a loose belt, a worn brush of a motor dust on a photosensor, etc, but the components have not failed. The advantage of defining more detailed degradation states is that we can accurately predict impacts on the failure of the components. A component can go through a series of degradation states before it fails. Samanta *et al.* [9] at Brookhaven National Laboratory developed a degradation model using a Markov approach to analyze historic component degradation rates and failure rate data for nuclear power plants. Most of the fault diagnosis research work is based on signature analysis of the process or component. To diagnose a fault from these recorded, sampled, and analysed data, expert systems and neural networks are two most popular approaches [5,6]. J.S. Lee [7] proposed the case based reasoning (CBR) method suitable for remote diagnosis and maintenance system.

There are two kinds of failures: (1) soft failure: a failure that can be corrected shortly after it occurs; (2) hard failure: a failure that caused the machine to be down for a long period of time. The conventional fault detection methods are: (1) modeling and parameter estimation; (2) discrete observation. Other methods includes finite automata state machine, PLC-based logic diagram, and simulation method. After researching degradation state and failure state, we can determine a better method on remote control and diagnosis of cluster tools.

三、研究方法

The development procedures can be summarized as follows. Firstly, four main state sets for maintenance procedure in a cluster tool are proposed. Secondly, the remote diagnosis system architecture is built. At last, the remote diagnosis system will be constructed.

1. Four main state sets for maintenance procedure in the cluster tool

The operational performance of components, machines, and process can be divided into four state sets:

(1) The normal operation state set

(2) The degraded state set

(3) Maintenance state set

(4) The failure state set

The definition of machine performance states is shown in Fig. 3

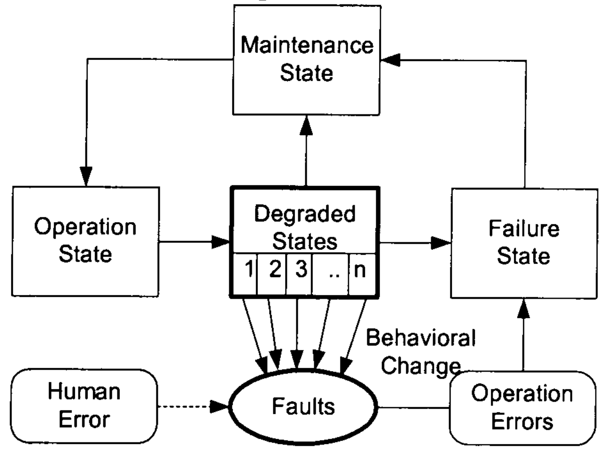

Fig. 3 Definition of machine performance state

For knowing more details of the cluster tool, more states and data should be collected. The states of the cluster tool are divided into two kinds: continuous and discrete states. The continuous states such as the pressure *P*, temperature *T* in the cluster tool, and processing time *t* in every chamber will be discretilized for the sake of convenience. Other discrete states, such as the state of doors *D* (open / close), the position of the robot arm *R* (extension / contraction), the state of chambers *C* (busy / idle), the thickness of wafers from ellipsometer θ, etc., will be collected to form a state set Φ as

$$\Phi=\{ P, T, t, D, R, C, \theta, ...\}$$

and Φ might be presented in its physical values, e.g. { 1.6, 20, 30.5, open, contraction, idle, 2.54, ...}.

From the historical data, we can summarize some states of the cluster tool, and determine these kinds of states to be degradation or failure. When the cluster tool is in the failure situation, the value of Φ will be classified as the failure state set, so is other state set. Engineers can easily determine the state set of the cluster tool. If the cluster tool is in the degraded state set or the failure state set, operators should process maintenance procedure until it is returned to the normal operation state set.

2. Construct Colored Timed Petri Net (CTPN) model of the cluster tool for maintenance and diagnosis

Maintenance and fault diagnoses play very important roles for the performance of the cluster tool. They affect the utility of machine, system performance, and cost, directly. In this section, the CTPN model will be applied to the modeling of the activities of fault diagnoses of machines and equipment maintenance in the cluster tool. The messages of the cluster tool including the devices and sensors can be collected properly. Such messages are helpful for maintenance engineers to detect the major problems of the system breakdown. In this manner, the engineers conclude the diagnosis results from their experience and knowledge as well as the messages from the sensors.

Data from sensors can be collected to a diagnosis system. In addition, CTPN will construct the logical relationships and experiences and knowledge of engineers from the fault tree. Thus, such CTPN-based diagnosis algorithm is similar to some functions of expert systems partly. The sensor based CTPN model can be used to model the fault tree and analyze the failure modes and effects analysis. Similarly, the CTPN-based fault diagnosis can be developed to identify the broken equipment (components, machines or cells).

Machines or equipment cannot work when they are broken-down or being maintained. Thus, the fault diagnosis and maintenance behavior of machines must be included in the CTPN model.

A fault tree is a common and convenient method to analyze the failure modes and effects, and it can identify the various possible failure modes and effects. The fault tree analysis aims to develop the structure from which simple logical relationships can be used to express the probabilistic relationships among the various events that lead to the failure of the system. The FMEA and fault diagnosis are both considered in the cluster tool. The sensor based CTPN is developed to model the FMEA from the fault tree, and model the fault diagnosis to identify the broken-down equipment.

In a factory, every sensor has its corresponding components. For example, level gauge corresponds to the tank, and pressure gauge corresponds to the pump. Thus, a sensor-based configuration is used to construct the fault tree. The events are defined as follows:

1. On-off sensors: by traditional PN
2. Analog sensors: divide the analog sensor value into appropriate levels, e.g., the value of level gauge can be classified into the HiHigh, High, Normal, Low, LoLow levels.

Based on the hierarchical and modular configurations, the CTPN can be used to construct the fault tree hierarchically. The CTPN elements such as places and transitions can be mapped with the fault tree elements. Some important fault tree symbols that relate to the cluster tool are selected in this project, such as AND gate, OR gate, condition gate, order AND gate, basic events, intermediate events, and transfer events. The transformation is described as follows:

1. Events, modeled by places
2. Gates, modeled by transitions
3. Complex systems, such as the cluster tool, modeled by hierarchical and modular configuration Fig. 4 shows the transformations between the CTPN models and the fault tree for the failure modes and effects applications. In Fig. 2, A, B and C are sensor recordings; T is the event; S1, S2, S3, S4 are the message communication places. Fig.5 shows the transformations between the CTPN and fault tree for the fault diagnosis application. In Fig. 5, A, B and C are sensor recordings; T is the event; EA, EB and EC are the diagnosis results, and they are corresponding to the sensors A, B and C.

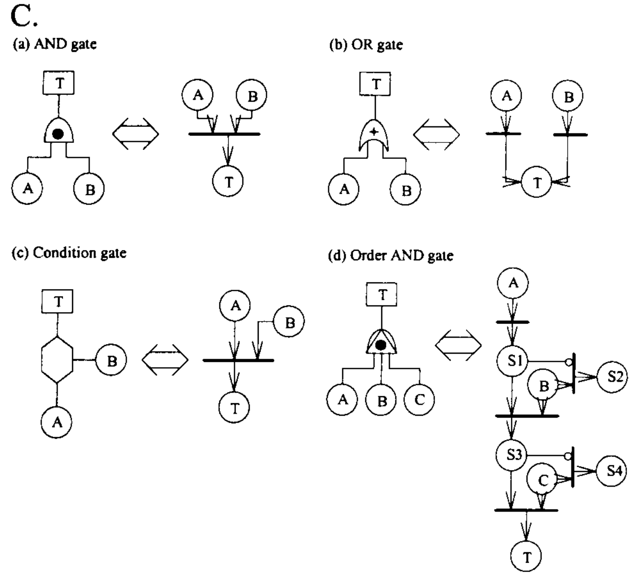

Fig. 4. The transformation between CTPN and fault tree for the failure modes

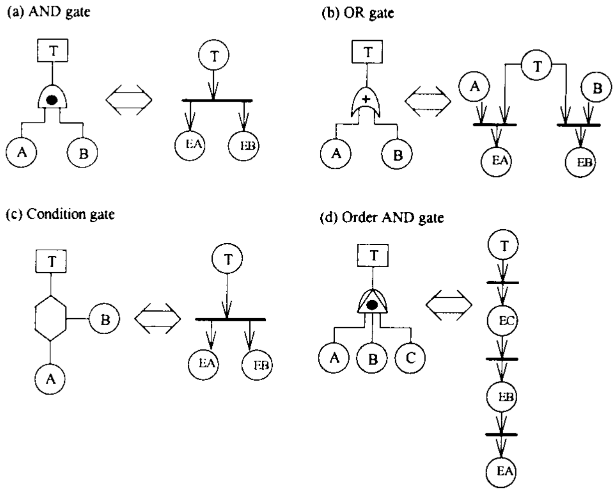

Fig. 5. The transformation between CTPN and fault tree for the fault diagnosis application

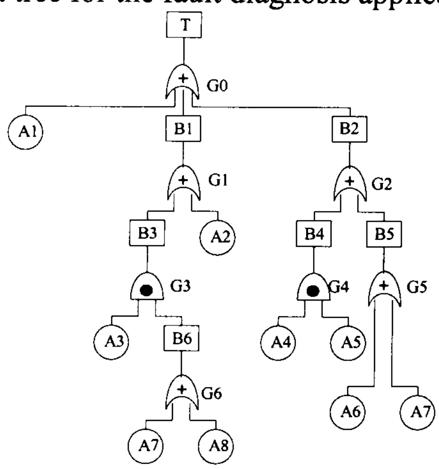

Fig. 6. An example of fault tree application

Clearly, the sensor-based CTPN can be used to model the fault diagnosis for identifying the broken equipment (components, machines or cells). Once the cluster tool is broken-down, the CTPN-based diagnosis can detect one or more possible defective components.

After researching all the faults and results, we can build up a fault tree for the cluster tool. There are three major faults can be detected in the cluster tool. They are process module, transfer module, and loadlock. The pressure in the transfer module and loadlock is one of the detection parameter.

3. The architecture of remote diagnosis system on the cluster tool

The architecture of remote diagnosis system for the cluster tool is three-tiered. Fig. 7 shows the relation of each tier. The first tier is the controller beside the cluster tool. The controller manages the data collected from the cluster tool, and preprocesses the data. When it detects the degraded state, the state will be transfer to the remote server, i.e., the second tier.

The second tier receives the preprocessed data from the first tier, and judge what state the cluster tool is. After determining the state of the cluster tool, the server will diagnose the data, and show all the methods we may use in the degradation or failure situation. Engineers can choose one of these methods to process maintenance procedure. The states and the solutions will be transferred to a web server.

In the third tier, operators can use generic browsers such as IE or Netscape to see what happens of the cluster tool.

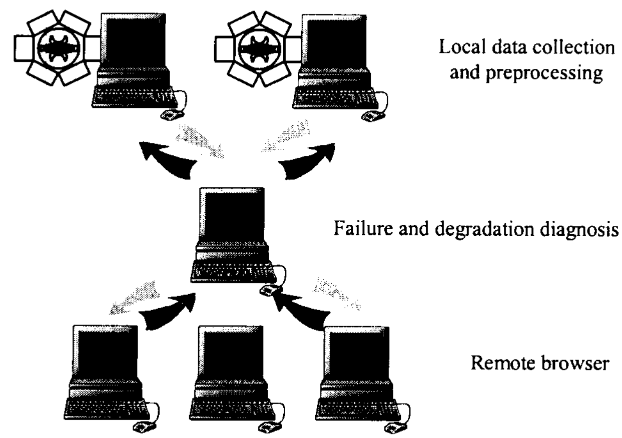

Fig. 7 The architecture of remote diagnosis system on the cluster tool

4. Constructing three tiers in the remote diagnosis system

After introducing the architecture of remote diagnosis system on the cluster tool, we will set the functions of all tiers.

The first tier: the sensing data will be transferred to a central server of the second tier through the Internet. If transferring the raw data directly, long time delays due to heavy traffic may be experienced. In addition, more storage space may be required in the central server. The data pre-processing for data collection and state determination needs to be addressed. The research emphasis here is on how to combine the engineering knowledge and diagnosis requirements in the data collection and pre-processing stages. Only meaningful data will be processed and transferred to the second tier. The controller of the first tier will store all the possible states and their classified state sets. When the degraded state set or the failure state set occurs, the processed data will be transferred to the remote server through Internet. When the cluster tool is in the normal operation state set, no data is sent to the second tier.

The second tier: when the server in the second tier receives data from the first tier, it will check the rule table to determine the current state set of the cluster tool. If the state set is the degraded state, the data will be marked yellow to indicate that the cluster needs to be maintained sooner or later. If the state set is the failure state, the data will be marked red to indicate the alarm condition. The cluster tool needs to be repaired immediately. All the data from the first tier will be analysed to determine the solutions for the degradation or failure of the cluster tool. We can collection two adjacent processed data from the first tier, and judge the event that drives this state to another. Fig. 8 is a simple example to show this concept.

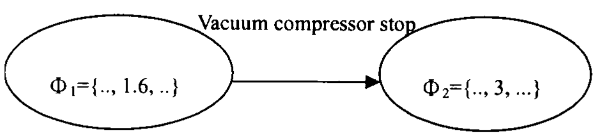

Fig. 8 A state is driven to another state by an event

When the possible events are recognized, the server will find out all the solutions to recover these events. The default solutions will be stored in the server.

All these states and solutions will be sent to a authorized web server. The web server will receive the replied choice of solutions from engineers, and send the solution back to the first tier if needed.

The third tier: the remote browser is the third tier. The engineers can use any computer connected to Internet to receive messages from the second tier. This computer can be anywhere outside the clean room, even at home. Since we use the technology of Active Server Page (ASP), people from the third tier can use any generic browser, such as IE or Netscape to connect the server of the second tier. Therefore, we need not develop extra client program. When the engineer see the degraded state or the failure state, he can choose a solution by himself, including clicks some buttons or sends e-mail from the computer, or takes a phone call, etc.

5. Preventive maintenance based on CMAC method

The structure of CMAC is shown in Fig. 9. It consists of 5 layers: input layer, sensor layer, association layer, post association layer, and output layer. From input vector **x** to output vector **y**, four mappings, Eqns. (1)-(3), should be performed.

Recall Process of CMAC

The recall process of CMAC consists of four mappings. The four mappings are introduced as follows.

(1) I→S: This is the mapping from the input layer to the sensor layer. Assume the input x is an n-dimension vector: x = (d1, d2, ..., dn). The mapping performs the following two steps:

Step 1: Quantize the input vector **x** to an integer vector $\mathbf{x_q} = (s_1, s_2, \ldots, s_n)$. Each $\mathbf{x_q}$'s component s_i, i=1, 2, ..., n, is the smallest integer greater than d_i.

Step 2: Activate *c* sensing elements of the corresponding sensor in the sensor layer. If the number of input is n, there are n sensors in the sensor layer, where each sensor corresponds to an input. Each sensor has a number of sensing elements and each sensing element senses an integer.

(2) S→A: This is the mapping from the sensor layer to the association layer. By concatenating the corresponding activated elements of the sensors in the input layer, *c* elements in the association layer will be activated. This mapping equips CMAC with the generalization capacity. When *c* increases or the resolution decreases, the generalization capacity increases, and vice versa.

(3) A→P: This is the mapping from the association layer to the post association layer. When the number of input or the resolutions of the sensors increase, the number of the required memory elements may be too large to be practical. The mapping from A to P is to reduce the number of the required memory. Hash-coding randomly and uniformly maps the elements in the association layer into the elements in the post association layer, where the size of the post association layer is much smaller than that of the association layer. The size reduction accomplished by hash-coding

should be properly designed so that the "collision" problem is small enough to be ignored. The collisions occur when hash-coding calculates the same address in the post association layer for two different memory elements in the association layer. The c elements activated in the association layer activate c elements for each output in the post association layer.

(4) P→O: This is the mapping from the post association layer to the output layer. Assume that the content of the activated elements for i^{th} output is ω_{ij}, $j = 1, 2, \ldots, c$, the value o_i of i^{th} output can be given by the following equation:

$$o_i = \sum_{j=1}^{c} \omega_{ij} \quad (1)$$

Learning Law of CMAC

The learning law of CMAC is presented as follows. Assume that the output of CMAC is **f(x)** when the input is **x**. For each training pair (x′, y′), the amount the output of the CMAC should be modified at each training-instant is:

$$\delta = \beta (\mathbf{y}' - \mathbf{f}(\mathbf{x}')) \quad (2)$$

where β is the learning rate and $0 \le \beta \le 1$. According to Eq. (2), the weights for output i should be modified by the following equation:

$$\omega_{ij}(k+1) = \omega_{ij}(k) + \delta_i / c \ , \ j = 1, 2, \ldots, c \quad (3)$$

where ω_{ij} is the j^{th} activated weight for i^{th} output, δ_i is the i^{th} component of δ and a scalar representing the amount that the i^{th} output should be modified, and k is a positive integer representing k^{th} training cycle. The learning law of CMAC can be further understood from Fig. 9.

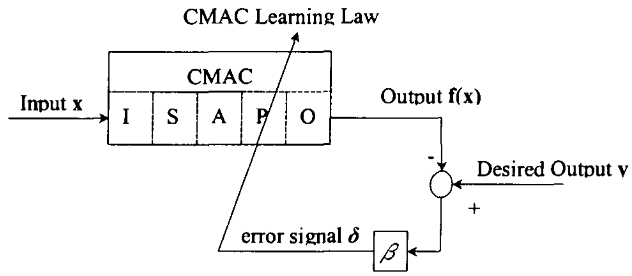

Fig. 9 The block diagram of the CMAC learning law

Considering Eqns. (1) ~ (3), it is evident that the recall process and learning law of CMAC are simple arithmetic operations and can be implemented in real-time. As to the convergence property of CMAC, Wong proved that CMAC learning always converges. This fact can be stated by the following theorem: From the learning of CMAC, we can predict the maintenance lead-time of the cluster tool. This approach is a useful technique for achieving proactive maintenance. The prediction will include:

- The pressure of the transfer module.
- The warn rate of the robot arm in the transfer module.
- The pressure in the load lock.

四、結論與成果

The Architecture of Remote Control System for Cluster Tools

The architecture of the remote control system of the cluster tool is three-tiered. Fig. 10 shows the relation of each tier. The first tier is a local controller. The controller manages the data collected from the cluster tools, and preprocesses the data. When it detects an error or failure, the message will be transferred to a central controller, i.e., the second tier. The second tier receives preprocessed data from the first tier, and judges the failure type of the cluster tool. After determining the failure of the cluster tool, the controller will diagnose the data, and show all the methods used in the failure analysis. Engineers can choose one of these methods to proceed to maintenance procedure. The status of the cluster tool and the solution will be sent to a web server. At the third tier, operators can use generic browsers, such as IE or Netscape, to see what happens to the cluster tool.

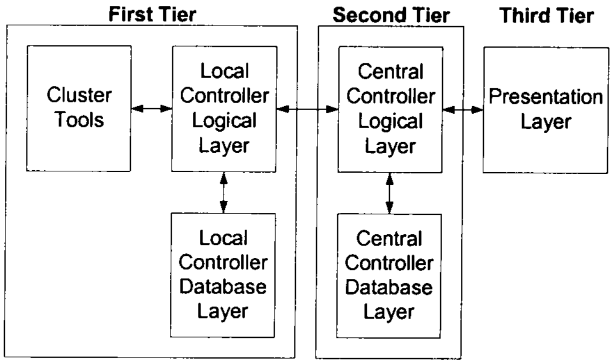

Fig. 10 The architecture of remote control system on cluster tools

Constructing Three-tiered Architecture of the Remote Control System

After introducing the architecture of the remote control system of the cluster tool, the functions of all tiers will be set.

- The First Tier

The sensing data is sent to the central controller through the Internet. For transferring the raw data directly, long time delays due to heavy traffic may be experienced. In addition, more storage space may be required in the central controller. One area that needs to be addressed is data pre-processing for data collection and error determination. The research emphasis here is how to determine the failure state in the data collection and pre-processing stages. Only meaningful data and messages will be processed and sent to the second tier. The controller of the first tier will store all possible states and their classified state sets. When an error or failure occurs, the processed data is sent to the remote controller through network. When the cluster tool is in the state of normal operation, only current status needs to be sent to the second tier, and the data will replace the historical data in the second tier.

- The Second Tier

Several servers constitute the second tier. When the controller of the second tier receives preprocessed data from the first tier, it will check the message type. If the message type is an error or failure, the message will be sent to the alarm server. The server will send the messages to the third tier, i.e., the remote presentation layer. There are several ways to inform operators the status of cluster tool (See Fig. 11). First, the message will be sent to a web server, so the message can be displayed on the remote browser which is inside the semiconductor foundry Fab or outside. Second, the server can also send an email to relevant operators, although there is no guarantee of immediate notice and correct reception of email. The third method is to send an essential message to the cellular phone.

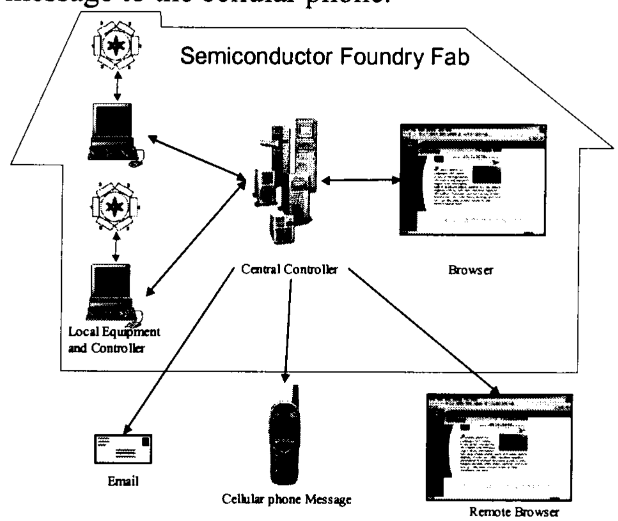

Fig. 11 The methods of noticing remote operators

The other server existing in the second tier is the diagnosis server. The diagnosis server deals with the message of errors and failure, and the construction of the diagnosis server is focused on the engineering knowledge and diagnosis requirements.

The web sever also exists in the second tier. The web server is the main interface to connect the second tier and the third tier. Error messages and diagnosis results will be sent to the third tier, and the command generated from the third tier will be received in the web server.

- The Third Tier

The remote browser is the third tier. The engineers can use any computer connected to Internet to receive messages from the second tier. This computer can be anywhere outside the clean room, such as home. There are no limits of space through Internet. Because the technology of Active Server Page (ASP) is used, the users from the third tier can use any generic browser, such as IE or Netscape, to connect the server in the second tier. Therefore, the extra client program need not be developed, and the third tier will show more flexibility. When the engineer sees the errors or the failure messages, he can choose a solution from a solution set by him or accept the solution generated by the diagnosis server in the second tier.

Message Flows in the Remote Control System

■ The First Tier

The message flows in the first tier are shown in Fig. 12. There are four main kinds of raw messages flowing from a cluster tool to the first tier, and after preprocessing, they will become a valuable data.

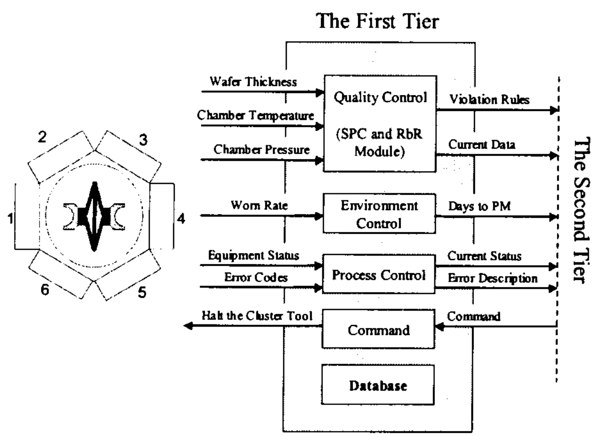

Fig. 12 The message flows in the first tier

There are four main kinds of messages sent to the second tier. They are (1) the quality of the products, (2) the condition of cluster tool, (3) process control, and (4) the vision monitoring of the local machine.

There are two major control responses of the cluster tool in the first tier. The first is the command sent from the second tier. The first tier is like a virtual machine, and transforms the command from the second tier to SECS-II format. When the transformation is complete, the message in SECS-II format will be sent to the cluster tool. For a remote control system, the most important command is to halt the equipment for preventing the next action to be proceeded. When the cluster tool prepares for manufacturing a wafer, the recipe of this wafer plays an important role to ensure the correct route. The second response is the determination of the wafer recipe.

There are three main states to represent the movement of the cluster tool. They are states of "Working", "Pause", and "Stop". The relation between states and commands is shown in Fig. 13.

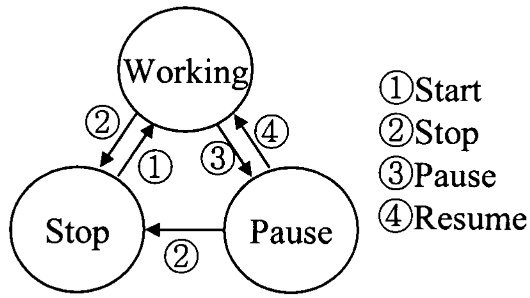

Fig. 13 The relation between states and commands

■ The Second Tier

The first tier of the remote control system is the local controller of the cluster tool, and the second tier is the central controller of the cluster tool. The central controller will receive the data from several local controllers; even local controllers are located in a foundry Fab as shown in Fig. 11. Because raw data have been preprocessed in the first tier, the data will not too huge to affect the efficiency of the central controllers when a central controller has to deal with messages from many local controllers. The message flows in the second tier are shown in Fig. 14. There are three servers to deal with the data flows, and five main preprocessed data sent from the first tier to the second tier.

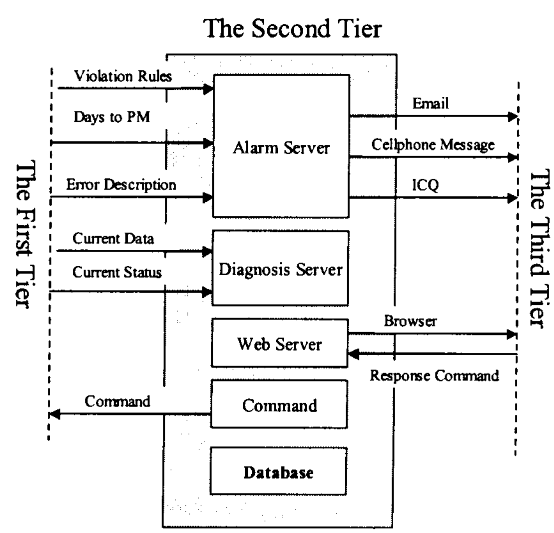

Fig. 14 The message flows in the second tier

The alarm server is a server to deal with the alarm procedure. The web server of the second tier conducts the data exchange of the web browsers. The diagnosis server will receive the symptom, which is equal to the alarm, and choose a most possible solution.

■ The Third Tier

Operators can receive the alarm message or other information from the second tier through the web browser, email, or cellular phone. When the operator has received the message, he will reply to confirm receiving. If the operator does not reply the message, the message will be sent again in a period of time. In addition to the confirmation reply, the operator can send commands to the second tier to control the cluster tool.

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