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Analysis of fast pressure control by the Ziegler-Nichols method for a transport module of a high vacuum cluster tool

Won Ick Jang, Jong Hyun Lee and Jong Tae Baek

Semiconductor Division, Electronics and Telecommunications Research Institute
Yusong P.O. Box 106, Taejon, Korea
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고진공 클러스터 장비의 반송모듈에 적용된 Ziegler-Nichols 방법에 의한 고속 압력제어에 관한 해석

장원익 · 이종현 · 백종태

한국전자통신연구소 반도체연구단
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Abstract – We have implemented a fast pressure control system for the transport chamber of a high vacuum cluster tool for advance semiconductor fabrication and evaluated its performance. To overcome the typically slow response of mass flow controllers, the modified experimental method is used very effectively to optimize the pressure control procedure. We successfully obtained quite fast pressure control by adjusting the starting time and the tuning constants by the Ziegler-Nichols method. In the transport pressure of 5×10^{-5} torr, actual pressure control starts from 4 sec after an initial gas load of 2.1 sccm. As a result, optimum conditions for the tuning constants are the rise rate of 0.02 torr/sec, the lag time of 0.15 sec, and the sampling period of 0.5 sec. Then the settling time is about 9 sec within about ±0.5% for the referenced value. This settling time is enhanced above 75 percents in comparison with conventional experimental method. To account for the experimental effects observed, a theoretical model was developed. This experimental result has a tendency to fit with the theoretical result of ω=-1.0.

요　약 – 차세대 반도체 제조공정을 위한 고진공 클러스터 장비용 반송모듈에 대해 고속 응답이 가능한 압력제어 장치의 구현과 그 성능시험을 수행하였다. 일반적인 자동 유량조절기가 가지고 있는 저속 응답에 대한 문제점을 해결하기 위하여 압력제어 순서을 매우 효과적으로 최적화하기 위하여 새로운 실험방법이 제시되었다. 압력제어를 시작하는 시점과 Ziegler-Nichols 제어방법에 의한 조율 상수들을 조절함으로써 매우 안정되고 빠른 응답이 가능한 압력제어를 성공적으로 달성하였다. 반송압력이 5×10^{-5} torr인 경우, 질소의 초기유량을 2.1 sccm으로 설정한 후 4초 시각부터 실제적인 압력제어가 시작되었다. 그 결과, 최대 압력오차가 설정값에 대해 ±0.5% 이하에서 안정화 시간은 10 sec 이내로 기존 실험방법과 비교해 볼때 70% 정도 개선된 우수한 성능을 얻을 수 있었다. 이때 rise rate는 0.02 torr/sec, the lag time는 0.15 sec, the sampling period는 0.5 sec 이였다. 이러한 실험결과를 설명하기 위하여 이론적인 모델이 유도되었으며, ω=-1.0일때 실험결과와 잘 일치함을 알 수 있었다.

I. Introduction

As devices become more complex and dimensions become smaller, contamination and native oxide formation due to atomspheric exposure may pose an increased threat to yield. Today a series of advanced semiconductor processes is being integrated via multi-chamber systems with a central transport module, that is called a cluster tool [1]. The use of the cluster tool has reduced fabrication costs and extended equipment cycles. In addition, it is very attractive that wafer transport from process to process is performed under high vacuum. But many particles can be generated from processes, equipment, materials, humans, and so on. All of these might contribute significantly to the generation of contaminated films. The main cause of contamination are not the cleanroom any more. As device complexities increase to ULSI (Ultra Large Scale Integrated Circuit) levels, the contamination induced by particles generated from process has become more important, even dominant[2]. The control of particle contamination is one of the main challenges on the way to ever higher integration in the production of advanced semiconductor devices. And there exists a rectangular slot valve between the transport and the process chambers for vacuum isolation. Most particles can be generated in the process chamber after actual semiconductor fabrication. On opening the slot valve between region of higher pressure in the range of 10^{-6} torr to the transport region of lower pressure in the range of 10^{-7} torr or less. Because the cluster tool is composed of various chambers, it is very important to effectively control the particle movements bwteeen chambers. Therefore, it is necessary to precisely control the vacuum level for wafer transportation between the transport module and cassete or process modules in a molecular flow range. Then the main problem is to shortening a large time-delay for the typically slow response of the mass flow controllers. To avoid excessive overswing or too a slow response to changes of the pressure setpoint, the analysis of the developed pressure control system is discussed.

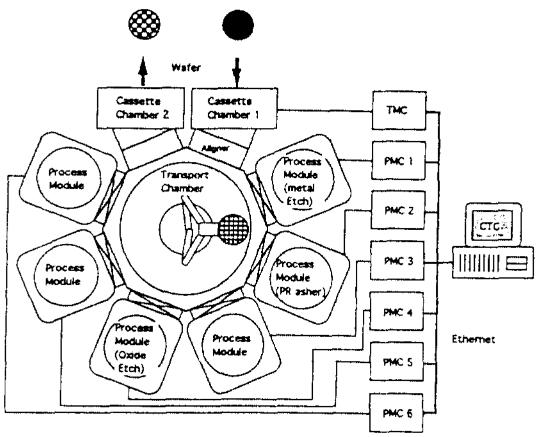

Fig. 1. Configuration of the cluster tool.

II. Experimental

Figure 1 shows the configuration of experimental apparatus for a SEMI (Semiconductor Equipment and Materials International)-compliant domestic cluster tool[3]. Each processing mdoule is mechanically and electrically independent and it has its own vacuum and control system. There are rectangular slot valves between modules, with acceptable pressure difference of 22.5 mtorr. The vacuum system of the transport module is composed of an ion gauge, a convectron gauge, isolation valves, a turbo-drag pump with its electronic drive, vacuum valves, a diaphargm pump, and a throttle valve with its controller. The ion gauge measures a high vacuum pressure below 10^{-3} torr, and the convectron gauge measures a low vacuum pressure between 760 and 10^{-3} torr.

The control system of the cluster tool is composed of a cluster tool controller (CTC), transport module controller (TMC) and process module controllers (PMCs). These are interconnected via an ethernet cable network. The CTC is the main controller that commands and schedules the TMC and PMCs and interacts with the operators. The TMC performs all the jobs related with wafer and cassette movements by controlling robot, aligner, cassette elevators, and various valves. Each PMC is dedicated to its own process module, such as metal and oxide etchers[4].

Figure 2 shows the schematic of the pressure control system for the transport chamber. To control the flow rate of nitrogen gas, the TMC calculates PID output by comparing a user-supplied

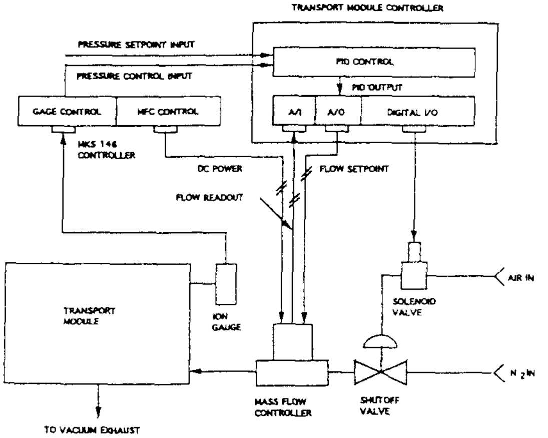

Fig. 2. Schematic of the pressure control system of the transport chamber.

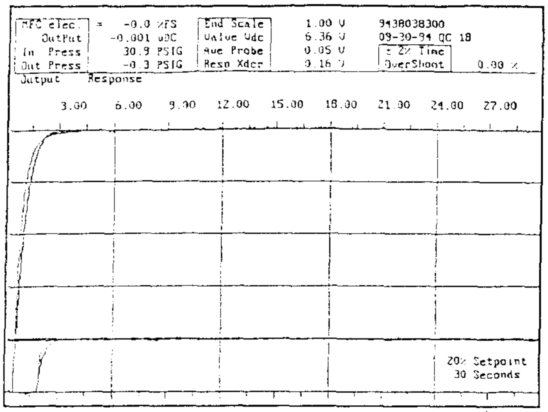

Fig. 3. Characteristic curves of the mass flow controller for nitrogen gas.

setpoint signal and a voltage signal from the ion gauge. Then MFC power is supplied by MFC control board in the MKS 146 controller. The inlet pressure of nitrogen gas is maintained at about 40 psi. Figure 3 shows the characteristic curves of the mass flow controller for nitrogen gas. We can see that the mass flow controller has a dead time of 1 sec. It takes 4 sec to stabilize within 2% for 20% and 100% setpoint of full scale.

III. Theoretical Background

A. Theoretical analysis.

In order to design vacuum and pressure control systems, we must utilize vacuum technology for the various components between process chamber and vacuum pump. If the pressure is low enough for molecular flow, the gas flow, Q, at the chamber can be expressed by the following equation.

$$Q=-V(dP/dt)+Q_G \quad (1)$$

We consider the total gas flow resulting from the various sources in a chamber.

$$Q_G=Qp+Ql+Qm+Qo \quad (2)$$

Where Q_G is total gas flow, Qp its artificial gas flow entering the chamber for process, Ql is gas flow which penetrates into the chamber as a result of leakage, Qm is gas flow entering the chamber by permeation through walls, and Qo is gas resulting from diffusion, vaporization and back streaming.

At very low pressure where the mean free path is much larger than the dimensions of the vacuum enclosure, the flow is molecular. In molecular flow, the value of the Knudsen number must satisfy the following condition:

$$D/\lambda < 1 \quad (3)$$

Where λ is the mean free path, and D is 16 cm, the diameter of the exhaust tube. For air, at ambient temperature the simple formula[5]

$$\lambda=5\times 10^{-3}/P \quad (4)$$

can be use, with P-torr and λ-cm. Where P indicates the average pressure in the chamber. By using equations (3) and (4), it results that the condition for molecular flow is $P<3.125\times 10^{-4}$ torr. Because it must have the value below 3.1×10^{-4} torr in a molecular flow, the initial values have been selected to 1×10^{-4} torr and 5×10^{-5} torr, to which it is possible to pump down the process module from process pressure within 10 sec.

From equation (2), if we neglect small quantities of Ql, Qm and Qo, the relation between the thorughput and the flow rate of the gas is empirically determined by the pressure-rise method.

$$1\ \mathrm{sccs}=1/60\ \mathrm{sccm}=0.76\ [\mathrm{torr}\cdot \mathrm{l/sec}]$$
$$Qp=\triangle P\cdot V/t_u[\mathrm{torr}\cdot \mathrm{l/sec}]=0.0127\cdot V' \qquad (5)$$

Where V is the volume of the chamber, V' is the volumetric flow rate, and t_u is the unit of time.

From these equations, we can establish the governing equation for wafer transportation in the molecular flow range. It becomes the following final differential equation,

$$C_1\cdot dP+[P+C_2+C_3\cdot Qp]dt=0$$
$$C_1=(1+Sp/C)/StV$$
$$C_2=-Po(1+Sp/C)$$
$$C_3=-(1+Sp/C)/St \qquad (6)$$

where C is total flow conductance, Po is the base pressure, St is the theoretical pumping speed, and Sp is the real pumping speed of the vacuum exhaust system. The time required for lowering the pressure in the chamber from Pi to P has two solutions according to the type of Qp.

1. *If* Qp=constant

If Qp is assumed cnstant, one can obtain the equation for the time required to reduce the pressure by integrating equation (6) using the variable separation method.

$$t=(V/St)\ [1+(Sp/C)\ \mathit{In}\ [(Pi-C_0)/(P-C_0)] \qquad (7)$$
$$P=(Pi-C_0)\cdot \mathit{exp}\ [(-V/St)t/\{1+(Sp/C)\}]+C_0$$
$$C_0=[1+(Sp/C)]Po+[1+(Sp/C)](Qp/St)$$

Where Pi is the value of an initial pressure in the chamber.

2. *If* Qp=f(t)

If Qp changes with the time, one can obtain the equation of time required to reduce the pressure at the chamber by converting the equation (6) to another type. We can represent Qp as the following equation by an experimental approach.

$$Qp=Qi(1-e^{-\omega t}) \qquad (8)$$

Where Qi is initial gas throughput.

After introducing equations (8) into (6),

$$dp/dt+P/C_1=f(t) \qquad (9)$$
$$f(t)=-C_5/C_1+C_4/C_1\cdot e^{-\omega t} \qquad (10)$$

This equation (9) is frist-order linear differential and non-homogeneous. The general solution can be represented as follows[6]:

$$P(t)=e^{-t/C1}[\int_0^t e^{t/c1}\cdot f(t)\,dt+C_6] \qquad (11)$$

Introducing equation (10) into (11),

$$P(t)=C_6\cdot e^{-t/C1}-C_5+[C_4/(1-\omega C_1)]\cdot e^{-\omega t} \qquad (12)$$
$$C_4=C_3\cdot Qi$$
$$C_5=C_2+C_3\cdot Qi=C_2+C_4$$

Because the initial condition is P=Pi at t=0, the constant C_6 can be obtained from equation (12).

$$C_6=Pi+C_5-[C_4/(1-\omega C_1)] \qquad (13)$$

After the time, t, the pressure reaches to the value as follows:

$$P=[Pi+C_5-C_4/(1-\omega C_1]\cdot e^{-t/C1}-C_5+[C_4/(1-\omega C_1)]\cdot e^{-\omega t}$$
$$t=[C_1/(1+\omega C_1)]\cdot \mathit{In}\ [Pi\cdot C_4/(1-\omega C_1)+C_4\cdot C_5/(1-\omega C_1)$$
$$-\{C_4/(1-\omega C_1)\}^2]/[C_5\cdot P] \qquad (14)$$

In this section, definitions of all symbols and numerical values for calculations are descibed in Table 1. Theoretical results will be discussed in the following paragraph.

B. Control agorithm.

Generally, the control system is divided in three parts. First part is the sensing part for the detection of physical properties to be controlled. Second part is the control part for the calculation of output from the error against the referenced value. Last part is the output part in order to control actual properties. The output of the system is based on the pressure error, which is the difference between the system's desired and actual outputs. The controller output is the weighted sum of the error, the integral of the error with time and the rate of the error change. Following is the continuous time equation for pressure control.

Table 1. Definitions and numerical values of parameters in theoretical analysis

parameter	unit	definition	numerical value
C	[1/sec]	total flow conductance	1680
C_0, C_1, ..., C_6	–	constants	–
D	[cm]	diameter of the exhaust tube	16
H	[cm]	height of the transport chamber	11.2
K_0, K_1, K_2, K_3	–	constants	–
L	[cm]	length of the exhaust tube	20
P	[torr]	vacuum pressure	1×10^{-4} or 5×10^{-5}
P_i	[torr]	initial pressure	760
P_0	[torr]	base pressure of the pump	1.333×10^{-12}
Q	[torr·/sec]	total gas throughput	variable
Q_i	[torr·/sec]	initial gas throughput	variable
Q_l	[torr·/sec]	gas throughput by leakage	negligible
Q_m	[torr·/sec]	gas throughput by permeation	negligible
Q_o	[torr·/sec]	gas throughput by diffusion, vaporization, back streaming etc.	negligible
R	[cm]	radius of the transport chamber	40
S_p	[1/sec]	real pumping speed	355
S_t	[1/sec]	treoretical pumping speed	450
t	[sec]	evacuation time	variable
t_u	[sec]	unit time	1
V	[1]	volume of the chamber	$\pi\cdot40^2\cdot11.2\cdot10^{-3}$
V'	[1/sec]	volumetric flow rate	variable
ω	–	index	–
λ	[cm]	mean free path	–

$$O(t)=K[E(t)+(1/Ti)\cdot\int E(t)\,dt+Td\cdot dE(t)/dt] \tag{15}$$

where O(t) represents the output, and E(t) represents the pressure error with time. the used closed loop control attempts to implement PID control using the Ziegler-Nichols method[7]. The output of this type of control is a weighted sum of the current error and last three error values. Actually the discrete type equation is applied.

$$O(t)=K_0\cdot E(t)+K_1\cdot E(t-1)+K_2\cdot E(t-2)+K_3\cdot E(t-3) \tag{16}$$

The values K, Ti and Td are callculated according to the following Zieglet-Nichols PID tuning rule,

$$\begin{aligned}&K=1.2/Gr\cdot Lt\\&Ti=2\cdot Lt\\&Td=Lt/2\end{aligned} \tag{17}$$

where Gr is the fastest rising slope of the open loop response, and Lt is the lag time of the response. The rise rate is the maximum of the measured rate of change, divided by the magnitude of the input step. The lag time is calculated from the maximum of the measured rise rate and where that point was measured.

The values of the constants, K_0 to K_3 are calculated by the transport module controller according to the measured lag time, rise rate of the open loop system and the sampling period,

$$\begin{aligned}&K_0=aK\\&K_1=\{b-(y-1)a\}K\\&K_2=\{c+ay-(y-1)K_1\}K\\&K_3=\{-yK_1-(y-1)K_2\}K\end{aligned} \tag{18}$$

where

$$\begin{aligned}&y=-\exp(-3Ts/Td)\\&a=1+(Td/Ts)\\&b=y-1+(Ts/Ti)-(2Td/Ts)\\&c=(yTs/Ti)+(Td/Ts)-y\end{aligned} \tag{19}$$

and Ts is sampling time. The sampling time is adjusted to feedback sufficiently by the mass flow controller.

The input parameter is the voltage signal of the ion gauge, that is 0 to 10 volts for 10^{-10} to 10^{0} torr. And the output parameter is the voltage signal of the mass flow controller, that is 0 to 5 volts for 0 to 5 sccm.

IV. Summary

To determine the full range of the mass flow controller, we calculate the pressure vs. time for several constant values Qp using equation (7). When the flow rates of nitrogen gas are Qp=0.0, 0.3, 1.5, and 3 sccm, the pressure variations as a function of time are given in Figure 4. In this analysis, we can see that the maximum admissible flow rate of the mass flow controller should be 5 sccm for wafer transportation.

In the meantime, we carried out preliminary experiments to be stabilized at some point as soon as possible. Many of experimental results are classified into three types with overshoot, undershoot and saturation to the reference value. Several results are compared with conventional method. Figrue 5 shows pressure variations as function of time for various parameters of Gr, Lt and Ts. Then the transport vacuum in 5×10^{-5} torr and the initial pressure of the transport chamber is 2.2×10^{-6} torr. As the lag time is shorter, the response time of the mass flow controller is faster. Also we can observe the phenomena of both overshoot and undershoot for the referenced value. The overshoot appears with proper adjustment of the rise time and the sampling period, but gradually disppears by increasing the lag time. In these conventional cases, the particles can be traveled because of sudden fluctuation of the pressure in the cluster tool. The best of settling time is about 20 sec within about ±1.0% for the referenced value. Then the rise rate is 0.02 torr/sec, the lag time is 0.25 sec, and the sampling period is 0.4 sec.

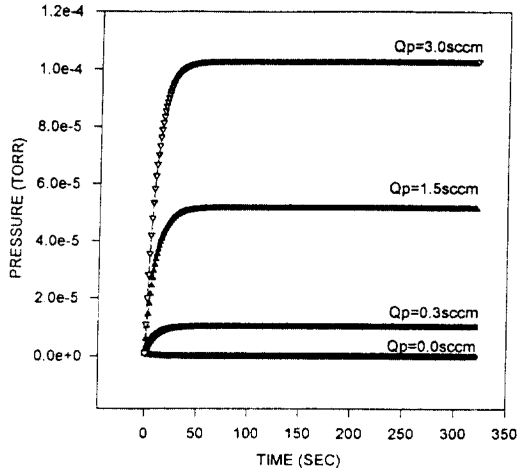

Fig. 4. The pressure variations versus for various constant values of Qp.

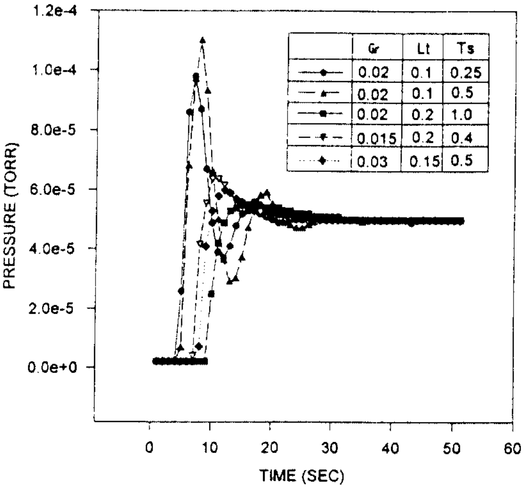

Fig. 5. Pressure variations as a function of time for various values of Gr, Lt and Ts at a transport vacuum of 5×10^{-5} torr.

From Figure 3, we conclude that the settling time within 2% for a setpoint requires about 4 sec including the delay time of 1 sec. Therefore we have tried modified experimental method in which the pressure control starts from 4 sec after an initial gas load. Figure 6 represents pressure variations by conventional and modified experimental methods. On applying the modified experimental

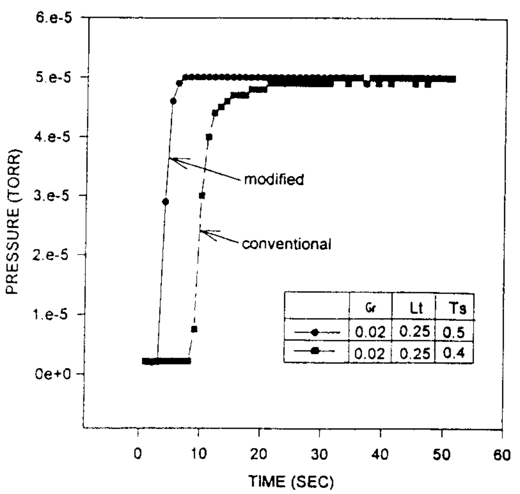

Fig. 6. Comparison for pressure variations by the conventional and modified experimental methods at a transport vacuum of 5×10^{-5} torr.

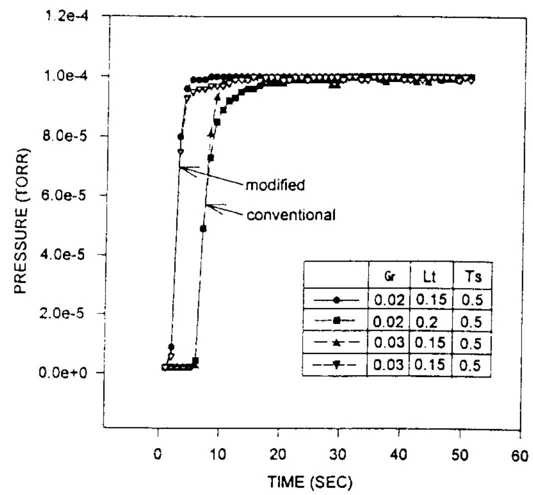

Fig. 8. Comparison for pressure variations by the conventional and modified experimental methods at a transport vacuum of 1×10^{-4} torr.

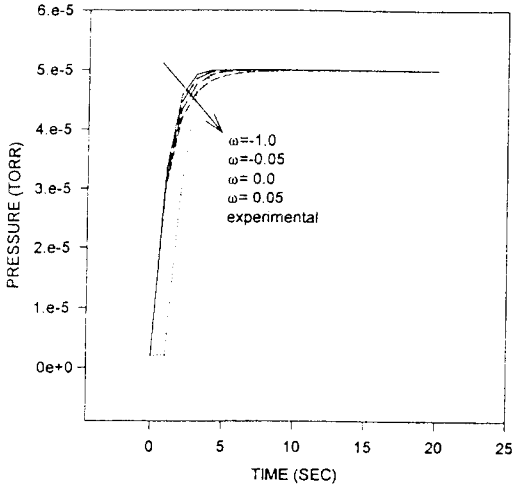

Fig. 7. Pressure variations with time for various index ω at a transport vacuum of 5×10^{-5} torr and Qi = 1.457 sccm.

method, the settling time have dramatically improved to about 8 sec within about ±1.0% for the referenced value. In the case of the transport vacuum of 5×10^{-5} torr, the rise rate is 0.02 torr/sec, the lag time is 0.25 sec. And the sampling period is 0.5 sec, the initial gas load of the nitrogen is 1 sccm. The settling time for modified experimental method is enhanced above 75 percents in comparison with conventional experimental method. From the same conditions, we have calculated pressure variations with time for the index ω, which varies from -1.0 to 0.05 as shown in Figure 7. The experimental result has a tendency to fit with the theoretical result of ω=-1.0. Because we neglected the residual gas remaining from leakage, outgassing and permeation in the simplifying step of assumptions, there are some differences between actual and theoretical values. Because of the delay time of the mass flow controller, the pressure gradient of the analysis is steeper than that of the experiment. But the measure for both cases becomes constant within about 9 sec.

Figure 8 shows pressure variations by conventional and modified experimental methods in the case of the transport vacuum of 1×10^{-4} torr. Optimum condition for the tuning constants in the modified method is the rise rate of 0.02 torr/sec, the lag time of 0.15 sec, the sampling period of 0.5 sec, and the initial gas load of 2.1 sccm. In this case, the settling time is about 9 sec within about ±0.5% for the referenced value. The maximum

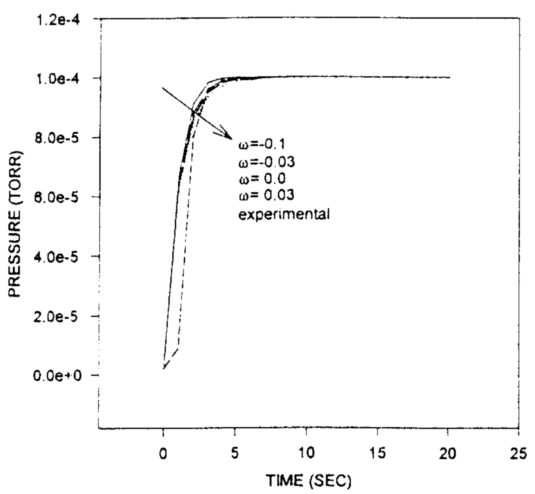

Fig. 9. Pressure variations with time for various index ω at a transport vacuum of 1×10^{-4} torr and Qi = 2.915 sccm.

variation of the pressure is 1.0×10^{-4} torr, which is the same as the desired output. At the same conditions, we can see that the modified method surpassed the conventional method in settling time. Figure 9 shows pressure variations with time as the index ω, which changes from -01 to 0.03. At the transport vacuum of 1×10^{-4} torr, the experimental result also has a tendency to fit with the theoretical result of ω=-0.03.

To reduce the contamination levels, it is advantageous to open and close the rectangular slot valve at the value of higher pressure. For wafer transportation, we have chosen and applied to the pressure of 5×10^{-5} torr in the transport chamber of the cluster tool. We can see that it prevented the transport chamber from back streaming of process gases from the process chambers.

V. Conclusion

In this study, we have developed a pressure control system for the cluster tool and evaluated its performance. The control algorithm is the Ziegler-Nichols method which considers the weighted sum of the last three error and current error values. We successfully obtained quite fast pressure control by adjusting the starting time with some initial gas load and the tuning constants in the control loop algorithm while taking into account the typically slow response of mass flow controller. In the case of the transport pressure of 5×10^{-5} torr, the settling time is less than 10 sec within about ±1.0% for the referenced pressure. This pressure control system prevented the transport chamber for back steaming of process gases from the process chambers. And cross-contamination between modules will be reduced by allowing wafers to be transferred at precisely controlled vacuum pressure.

To evaluate the effectiveness of the developed pressure control system, we are planning to quantitatively measure the particle contamination contributed by the transport and process modules.

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