Study of High-tech Process Furnace using Inherently Safer Design Strategies (III) Advanced Thin Film Process and Reduction of Power Consumption

Chih-Cheng Lu¹, Kuo-Chi Chang¹, Chun-Yu Chen^{*2}

¹ Institute of Mechanical and Electrical, Taipei University of Technology, Taipei 10608, Taiwan, ROC

^{*2} College of Design, Vanung University, Tao-Yuan City 32061, Taiwan, ROC

Abstract

Semiconductor manufacturing is the economic backbone of Taiwan. Although efforts have been made to improve production capacity and achieve full load production, manufacturers are still unable to effectively control the power consumption situation during the failure of full load production due to special circumstances. Those processes do not conform to the characteristics of inherently safer design, which increases process risks. The objective of this research was to investigate the effects of power consumption reduction on the process furnace, maintaining the same production capacity in the existing 22nm advanced semiconductor process. In this study, TEOS was used as the raw material for LPCVD process simulation, experimentation, and exploration. The adopted LPCVD reactor was of the commercial batch type; the process experiments simulated the IPD process applied on the 22nm MOSFET, with a thickness of 5000Å and process time of 60 min. The simulation results of different batches were compared with the experimental values, and the simulation values were consistent with the experimental values by adjusting the different k_a values. The reactor contained processes for 125 wafers and 100 wafers. According to the simulation and experimental results, the thin film deposition results were acceptable. Finally, the heating zone output current was explored specifically for two batches of wafers in the 12" furnace tube process. In the process of the first batch, as there were only 100 wafers, 18.05A was reduced by shutting off the 5th heating zone. The machine had a voltage of 220V and converted power output up to 3971W, accounting for 26% (15265.8W) of the entire machine. This significantly reduced power supply of the entire machine and hazard potential, which is consistent with the characteristics of inherently safer design. Moreover, there were fifteen 12" tube furnace machines in the experimental workshop of this study, and shutting off unnecessary heating zones could reduce 59565W/H of the power supply and hazard potential. **Finally, the 12" tube film process machine electrical hazards and damage control measures were analyzed by using FMEA method, and confirmed that the research results were in line with the expected attenuation strategy of ISD. This approach has increased the safety level, but also reduced operating costs, which is an important achievement of this study.**

Keywords: Inherently Safer Design, LPCVD, Thin Film deposition, 22nm IC process, Reduction of Power Consumption, **FMEA**.

List of the Acronyms

1. STI: Shallow Trench Isolation
2. TEOS, $\text{Si}(\text{OC}_2\text{H}_5)_4$: Tetraethyl Orthosilicate
3. IPD: Inter-Poly Dielectric
4. MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor
5. LPCVD: Low Pressure Chemical Vapor Deposition
6. CD: critical dimensions
7. ILD: Inter Layer Dielectric
8. PMD: Pre-Metal Dielectric
9. IMD: Isolation Metal Dielectric
10. T: temperature
11. MF: mole fraction
12. F: flow rate
13. P: pressure
14. PR: Photo Resist
15. FMEA: Failure Mode and Effects Analysis
16. ○: Experiment result
17. Δ: modified result

1. Introduction

Semiconductor manufacturing is the economic backbone of Taiwan. Although efforts have been made to improve production capacity and achieve full load production, manufacturers still cannot effectively control the power consumption situation during the failure of full load production due to special circumstances. This increases the process risks and fails to meet the spirit of inherently safer design. Under the influence of the global financial crisis of 2008, Taiwan's semiconductor manufacturers have significantly reduced production capacity. Consequently, in the processing of numerous batches, while only a part of the pieces can be put into production, all process parameters are enabled. Taking LPCVD for example (as shown in [Figure 1](#)), the 12" furnace tube machine is the batch process and the number of wafers in each batch process is 150. If the production capacity utilization rate is 70%, then 105 wafers are put into production in each batch; however, the process parameters of the process machine of each batch must be comprehensively considered, as the enterprises are unable to effectively develop the process parameter control scheme. Regarding thin film deposition, temperature is an important process control parameter. Some studies have estimated the simulation results of the influence on process temperature distribution by shutting off heating zones ([Chen et al., 2013a](#)).

For the LPCVD process, the main process parameters include T, MF, F, and P. Among the parameters, temperature has the most affect on the thin film deposition rate, thus, it is the most important process parameter ([Chen et al., 2013b](#)); however, most current 12" LPCVD vertical furnace tube machines are

designed with five heating zones, as shown in **Figure 1**. In the timing sequence of temperature control, the temperature of the furnace tube heating zone is first improved and transferred to the center of the furnace tube, thereby enabling wafer temperature to rise. When the temperature and heating time reach the set values, the reaction gas would be introduced into the reactor of the furnace tube for reaction, as shown in **Figure 2** (Harbeke et al., 1984). However, for process stability, most manufacturers do not make any changes after the temperature control is set, regardless of the number of wafers put into the process, even when an excessive power supply would result in additional and unnecessary risks. This does not meet the concept of inherently safer design (Khan and Amyotte, 2004; Kletz and Amyotte, 2012; Chen et al., 2014).

In the current 22nm advanced semiconductor process, although no significant changes are made in the element principle, various new research findings are added to actual commercial production in order to seek the gradual reduction of Critical Dimension (CD). As shown in **Figure 3**, in the current 22nm advanced semiconductor process product structure, the main process changes are those made based on product structure changes, including the STI production of elements (Sze and Ng, 2006), production regarding the heavy doping of SiC and SiGe to change the structural pull stress layer or compress stress layer (Biela et al., 2011; Avenier et al., 2009), the structural design regarding gate width reduction, the process application of high-K materials (Gusev et al., 2001), and the application of self-aligned structures (Stutzmann et al., 2003; Liao et al., 2010). The integration design of element processes and analysis of safety and health management issues are summarized in **Table 1**.

The equipment structure can be modified specific to advanced 22nm process changes, as based on process requirements; thereby affecting the potential hazards of the process machine (Zhou., 2010). Therefore, this study conducted analysis hazards in advanced 22nm IC process, equipment, and facility system, and the results are shown in Table 2. As seen, high-temperature, gas leaks, fires, explosions, shocks, rolling and crimping, organic solvent poisoning, acid and alkali corrosion, hitting, and cutting are hazardous items that require particular attention in the advanced semiconductor process. Since the process determines the structure and function of the machine and equipment, from a safety point of view, the safety level could be inherently changed if changes are made in the process to render workshop operations safer.

Temperature control purpose is to meet the needs for the successful completion of process requirements. So this study began to explore a thin-film process using 12" furnace to analyze the temperature control to meet the expected process conditions, and then established an effective control mechanism to allow the temperature power consumption, which could be reduced in order to reach the essence of inherently safer design (ISD) strategies. Concepts and mechanism analysis of this study could be used for the safety and health management staff in various similar machines. It is the important contribution of this study, including with the effectiveness of both safety and operation cost down.

2. Methodology

This study started from 12 " furnace to achieve advanced 22nm thin-film process, then the process requirements could be satisfied by using the further analysis of temperature control, and finally applied the ISD strategies to discuss energy consumption.

Although many changes have been made in the **advanced 22nm IC process**, the deposition of SiO₂ remains an important process for most products, and is adopted by STI, ILD layer, Sidewall Spacer layer, PMD layer, and IMD layer, and continued exploration of such processes is necessary (Faccio et al., 2008). Chen et al. (2013a) (2013b) applied the method proposed by He et al. (2003) onto the horizontal LPCVD reactor of the 6" wafer process, and used the thermal radiation configuration factor to correct the practice of Badgwell et al. (1994), in order to establish a set of steady-state linear relationships of the furnace tube and wafer temperatures. They also adopted the method proposed by Kim and Kim (1999) to study and simulate the temperature distribution model and process effects. The reaction mechanism, as mentioned by Jensen and Graves (1983), was used to establish the deposited film thickness model, and conduct simulation and verification using SiH₄ to deposit Poly-Si. Table 3 shows the CVD thin film materials used in the semiconductor summarized in this study. Table 4 shows the CVD related materials and deposition methods (Sze and Ng, 2006).

In this study, Tetraethyl Orthosilicate (TEOS, Si (OC₂H₅)₄) was used as the raw material. TEOS is an organic molecule that has high surface mobility. CVD thin film deposition, as based on TEOS. It generally has good step coverage and trench filling ability, and is widely used in the deposition of oxide, including STI, sidewall spacer, PMD, and IMD. TEOS is in the liquid state at room temperature and atmospheric pressure. During application, heating the TEOS container (about 40~70°C) increases its saturated vapor pressure for the convenience of application in the gas state. As TEOS has a very high boiling point (about 169 at atmospheric pressure), in the CVD process application and under high temperature, TEOS can only have the reaction of Eq. (1) due to its need for adequate heat in order to further generate the SiO₂ resultant. As a result, the furnace tube is commonly used for this process. Eq. (1) uses the reaction formula of TEOS generating SiO₂ (Desu et al., 1989; Huang et al., 2003).

From Eq. (1) and Desu et al. (1989), the reaction kinetics for SiO₂ were shown in Eq. (2), (3), and (4):

1. TEOS decomposition in gas phase:

2. Adsorption reaction:

3. Surface chemical reaction:

The deposition reaction rate:

$$r = \frac{k_d K_a (K_g C)^{0.5}}{1 + K_a (K_g C)^{0.5}} \left(\frac{\text{mole}}{\text{cm}^2 \cdot \text{s}} \right) \quad (5)$$

where

r : deposition reaction rate $\left(\frac{\text{mole}}{\text{cm}^2 \cdot \text{s}} \right)$

C : TEOS gas concentration $\left(\frac{\text{mole}}{\text{cm}^3} \right)$

R : gas constant

T : reaction temperature (K)

$$K_g = 1.38 \cdot 10^4 \exp\left(-\frac{299240}{8.314T}\right) \left(\frac{\text{mol}}{\text{cm}^3} \right) \quad (6)$$

$$K_a = 1.14 \cdot 10^{10} \exp\left(-\frac{21422}{8.314T}\right) \left(\frac{\text{cm}^3}{\text{mol}} \right) \quad (7)$$

$$k_d = 4.74 \cdot 10^{-8} \exp\left(-\frac{12259}{8.314T}\right) \left(\frac{\text{mol}}{\text{cm}^2 \cdot \text{s}} \right) \quad (8)$$

The assumed conditions of this study are as follows:

1. 1-D mode.
2. The thin film deposition of the isotropic phase is uniform.
3. The reaction occurs only on the effective area.
4. Isotropic thin film deposition.
5. The temperatures of wafers are uniform.
6. TEOS is plug flow.
7. The trench reaction deposition is not considered.

The LPCVD reactor adopted in this study was of the commercial batch type (ASM a412); 148 chips could be put in the reactor each time, including 125 pieces of wafers, 20 pieces of blank pieces, and 3 pieces of test pieces. The 3 test pieces were No. 14, 70, and 134, which are counted from the bottom of the LPCVD reactor. After each process was completed, the thickness of the thin film on these three test pieces was

measured, which was not performed on other wafers to obtain the wafer thickness at these 3 locations. The wafer used in the process was 12 inches (300mm) and operated under 0.6 torr pressure. The reactor had a diameter of 435mm and a length of 1215mm. The rotation speed of the cassette was 2rpm; and the feed flow rate of TEOS was 380sccm. The process experiments simulated the IPD process applied on the 22nm MOSFETs, with a thickness of 5000Å and process time of 60 minutes. The status data within the LPCVD reactor of this study are as shown in [Table 5](#).

In this study, process capacity comparison was conducted through simulation and actual testing in order to confirm that the process capacity is able to maintain the desired target in the case of process parameter changes. As temperature is the most important process parameter of thin film deposition, this study focused on adjustment of the 5th heating zone of the 12" furnace tube under the condition that other factors, such as the mf, F, and P, remain unchanged.

Based on the thin film deposition processes of different process wafer numbers, it is important to grasp temperature control for decreased number of wafers, in order to reduce the input power of the machine and equipment. This can satisfy the attenuation design strategy in an inherently safer design, which can reduce the hazard of machine and equipment. The monitoring method of the temperatures of the five heating zones of the machine in this study is as shown in [Figure 4](#). The temperature monitoring started from the element control panel, as its power was supplied to the power supply unit, which can control the power of each heating zone through the thyristor (as shown in [Figure 5](#)). [Figure 6](#) shows the condition when only 60% power was input to a heating zone. The temperature control circuit of the experimental and test machine in this study is as shown in [Figure 7](#) ([ASM, 2013](#)).

As regards the [ISD strategy of attenuation](#), when the process piece number began to decrease from the full load, under the condition that the requirements of the desired process target could still be maintained, reducing the power input of heating zone could significantly reduce the power hazard, as well as other unnecessary hazards.

[In the main framework of this study, the use of FMEA analysis was applied to the 12 "tube film process machine electrical hazards and damage control measures. Comparisons and discussion on the final analysis with those of the results of major research were made to double confirm the research outcome, which is consistent with the expectation in weakness of ISD strategy.](#)

3. Film deposition process simulation and experiment

Without considering the chip trench area, the simulation, experimentation, and comparison were conducted based on the assumption that the pieces in a group of LPCVD reactor of 12" furnace tube are all blank pieces. The kg, ka, and kd values were from literature, as shown in Eq. (9). Regression analysis was conducted through the simulation, experimentation, and comparison of blank pieces. The results are the values shown in Eq. (10), which are used for subsequent experimentation and discussion ([Desu et al.,1989](#); [Huang et al., 2003](#)).

$$\begin{cases} K_g = 1.38 \times 10^4 \exp(-299240/8.314T) \\ K_a = 1.14 \times 10^{10} \exp(-21422/8.314T) \\ k_d = 4.74 \times 10^{-8} \exp(-12259/8.314T) \end{cases} \quad (9)$$

$$\begin{cases} K_g = 1.38 \times 10^4 \exp(-299240/8.314T) \\ K_a = 1.14 \times 10^{10} \exp(-21422/8.314T) \\ k_d = 3.5370 \times 10^{-8} \exp(-11700/8.314T) \end{cases} \quad (10)$$

Figure 8 shows the results after regression. A comparison was made between the thicknesses of the 5 blank wafers measured in the field. The results were obtained through simulation of the established physical model. Regression of the reaction kinetics formula of the deposition reaction was then conducted. Eq. (9) is the reaction kinetics formula, based on previous literature. The reaction kinetics formula of Eq. (10) can be obtained after regression is conducted. According to a comparison of Eqs. (9) and (10), only the K_d value presents some small differences in the data after regression. In **Figure 8**, the red dot denotes the field-measured data, while the black line denotes the result of simulation. The simulation result and experimental data are consistent. From the diagram of the TEOS reaction rate and temperature in **Figure 9**, the symbols: $\circ$ (Experiment) Δ (modified). The difference is very little, suggesting that there is little change in the reaction kinetics formula through regression and the reaction kinetics formula of literature.

In this study, simulation and experiments were conducted at the TESO feed flow rate of 380sccm. The TESO feed flow rate could be divided into two types, 380sccm and 230sccm. The wafer number inside the reactor could be divided into 125 wafers and 100 wafers after reduction, respectively. Simulation with the data of the TESO feed flow rate of 380sccm was conducted first. If the memory size of the chip cut from the wafer were 256MB, the trench area of the wafer must be considered when calculating the reaction area. **Figures 10** and **11** show the comparison of the simulation results and experimental values of different batches. The simulation values and experimental values were made consistent with each other by adjusting the different k_a values. The reactor contained the processes for 125 wafers and 100 wafers. The difference between **Figures 10** and **11** revealed that the reaction area after piece No. 110 was very small, as shown in **Figure 10**, as only blank wafers were placed after it. In **Figure 11**, as it is fully filled with 125 wafers, the blank wafers only appeared after piece No. 131. According to the simulation and experimental results in **Figures 10** and **11**, the thin film deposition results were acceptable. **Figure 12** shows the SEM results after thin film deposition and thickness confirmation by etching. In order to clearly see the deposited film thickness, wet etching was performed after the surface was applied with PR, thus, the IPD thickness after the deposition reaches 5009Å met the process requirements.

4. Discussion of power hazard elimination and control on ISD strategies and FMEA analysis

The hazard of the most concerned in the thin film deposition process is the power hazard; therefore, temperature control in the process is very important. Especially in the case of a reduction in the number of

pieces in the process, the effective power input reduction is bound to significantly improve the inherently safer **level** of the process machine. Most studies on power supply discuss the economic subjects, such as energy consumption saving (Shnayder et al., 2004; Carroll, 2010; Kirousis et al., 2000), but there lacks discussion on safety, such as the power hazard. There are scanty studies on the dispatching safety of system energy consumption (Kocher et al., 1999). Therefore, it is necessary to explore the power hazard from **the point of view of ISD**. The detailed temperature change conditions specific to the process machine selected in this study were explored. The temperature changes of a single heating zone are as shown in **Figure 13**. As seen, the thermometer captured the temperature value once per second, and the average power input was adjusted every 2 min. Thus, when the temperature was set to 700 ℃, the power input was effectively controlled within the range of $\pm 0.5 \text{ W}$, meaning the process temperature is able to meet the desired target.

In this study, the heating zone output current is explored specific to the aforementioned two batches of wafers in the 12" furnace tube process, with the results as shown in **Tables 6 and 7**. In the process of the first batch (**Table 6**), as there are only 100 wafers, the 5th heating zone is shut off and the discussed desired process target is attained. Therefore, 18.05A can be reduced by shutting off the 5th heating zone. The machine had a voltage of 220V and converted power output up to 3971W, accounting for 26% (15265.8W) of the entire machine, indicating significantly reduced power supply of the entire machine and hazard potential. This is consistent with the characteristics of inherently safer design. Moreover, there were fifteen 12" furnace tube machines in the experimental workshop of this study, and shutting off unnecessary heating zones could reduce 59565W/H of the power supply, thus, lessening the hazard potential.

In Taiwan, due to the limited workshop layout area, the process machines are densely arranged, resulting in a very high combustible density per unit area. Moreover, a large number of supply lines are arranged closely in the clean room and auxiliary clean room according to the process needs. Although the temperature abnormalities resulted from a loose connection and insulation deterioration could be discovered by infrared detection during safety patrol inspections of the machines and equipment at the ordinary times (as shown in **Figure 14**) (Lin, 2002; Chen et al., 2013), many electrical circuits are hidden in the depths of the machines and equipment, constituting continued difficulties in safety management. Regarding the electric power system, the inherently safer strategy of shutting down heating zones should be implemented in the case of production reduction in process planning in order to reduce the power supply and further reduce the combustion of heating zone contacts (as shown in **Figure 15**). **In this study, the current process temperature supply and control system for commercial operation machine of accident statistics (please refer Figure 4 of the temperature control framework), found that the heating zones element contacts most often occurred due to not lock to the proper torque that caused by the ohm contact is too large and would caused overheating short circuit explosion, as show in Figure 15 of (c) photos. Therefore, if in the process reduction of production, properly closing the no effect of the process of heating zones will effectively reduce the operating current of the heating element. The contacting heat could also be reduced simultaneously, and the more inherently safer level would be increased dramatically.**

In order to ensure compliance with the preceding main results of risk assessment , FMEA methods were applied to 12 " tube machine temperature control system for analysis in this study , the results as shown in Table 8. From the experimental results showed that Heating elements No. 1 to 5 were as the most

prone to failure and after the failure of the most serious damage. If more deeply explored the reasons, because of insufficient torque fixed terminals when the heating element was installed, resulting in ohmic contact resistance was too large, further leading to the contact heat, and finally contacts burning or explosion. In lighter condition, would impact on the process shutdown and warning light action; in severe condition, cause the smoke early detectors warning system action, and then withdraw the whole plant, or contacts explosion cause a high-tech factory fire. Therefore, if in the production process, the effective closure of the unnecessary heating zone, the overall process tool operating current decreases. These satisfied the attenuation strategy of ISD, eliminating the risk of the aforementioned short-circuit and contact point explosion, and improving the overall plant safety. This argument was fully consistent with those of the impact and consequences in Figure 15 of (c) photos.

From the foregoing discussion, some important suggestions on the LPCVD process should have the following practices:

- (1) In the request to maintain the process, maximizing the use of non-combustible liquid or chemicals to reduce the overall machine fire and explosion possibilities.
- (2) In the process of full load, the anomalous temperature monitoring device of heating control loop should be implemented and timely linkage to interrupt the process while occurring the chain reaction could be reduced.
- (3) In the manufacturing process was not fully loaded, the machine heating control loop could automatically turn off the non-heating zone heater function, reducing the overall machine power usage, and then eliminating the risk of fire and explosion from the heating sources.
- (4) The machine exhaust system of non-manufacturing process should be readily linked process heating systems. When the failure in exhaust system led to the external environment flammable gases entering the interior of furnace tube machine, process heating system should be able to automatically turn off the heating function, and then the heat sources of fire and explosion could be eliminated.

5. Conclusions

The current process changes of the 22nm advanced semiconductor include the STI production of elements, production regarding the heavy doping of SiC and SiGe to change the structural pull stress layer or compress stress layer, the structural design regarding gate width reduction, the process application of high-K material, the application of self-aligned structures, and the integration design of element processes. In addition, high-temperatures, gas leaks, fires, explosions, shocks, rolling and crimping, organic solvent poisoning, acid and alkali corrosion, hitting, and cutting are the hazardous items that require particular attention in advanced semiconductor processes.

Although many changes have been made in advanced semiconductor processes, the deposition of SiO₂ remains an important process for most products, and is adopted by the STI, ILD layer, Sidewall Spacer layer, PMD layer, and IMD layer. Continued exploration of the process remains necessary. In this study, TEOS

was used as the raw material for LPCVD process simulation, experimentation, and exploration. The LPCVD reactor adopted in this study was of the commercial batch type (ASM a412); 148 chips were put in the reactor each time, including 125 pieces of wafers, 20 pieces of blank pieces, and 3 pieces of test pieces. The 3 test pieces were No. 14, 70, and 134, which were counted from the bottom of the LPCVD reactor. The wafer used in the process was 12 inches (300mm) and operated under 0.6 torr pressure. The reactor had a diameter of 435mm and a length of 1215mm. The rotation speed of the cassette was 2rpm, and the feed flow rate of TEOS was 380sccm. The process experiments simulated the IPD process applied on the 22nm MOSFETs, with a thickness of 5000Å and process time of 60 min. The simulation results of different batches were compared with the experimental values, and the simulation values were consistent with the experimental values by adjusting the different k_a values. The reactor contained the processes for 125 wafers and 100 wafers. According to the simulation and experimental results, the thin film deposition results are acceptable.

The heating zone output current was explored specific to two batches of wafers in the 12" furnace tube process. In the process of the first batch, as there were only 100 wafers, the 5th heating zone was shut off, and 18.05A was reduced. The machine had a voltage of 220V, and a converted power output up to 3971W, accounting for 26% (15265.8W) of the entire machine. The power supply of both the machine and hazard potential was significantly reduced, which is consistent with the characteristics of an inherently safer design. Moreover, there were fifteen 12" furnace tube machines in the experimental workshop of this study, and shutting off unnecessary heating zones could reduce 59565W/H of power supply, thus, reducing the hazard potential. **Finally, the 12 " tube film process machine electrical hazards and damage control measures were analyzed by using FMEA method, and confirmed that the research results were in line with the expected attenuation strategy of ISD.**

In Taiwan, due to the limited workshop layout area, the process machines are densely arranged. In addition to infrared detection during the safety patrol inspection of the machines and equipment at ordinary times, for the electric power system, the inherently safer strategy of shutting of the heating zones is implemented for production reduction during process planning in order to reduce the power supply, and further reduce the combustion of heating zone contacts. Based on the chemical process safety management architecture, as proposed by [Hendershot \(1997\)](#), it is found that inherently safer design strategies, such as the intensification, substitution, attenuation, and limitation of effects, could be applied specifically to the process design, in order to fundamentally eliminate the hazard potentials and significantly increase the overall safety level of the workshop (as shown in [Figure 16](#)).

Acknowledgement

Funding for this investigation was provided by National Science Foundation, Taiwan, ROC. Under grant number **NSC102-2622-E-238-008-CC3**.

References

1. ASM Company. (2013). a412 Installation manual.

2. Avenier, G., Diop, M., Chevalier, P., Troillard, G., Loubet, N., Bouvier, J., Depoyan, L., Derrier, N., Buczeko, M., Leyris, C., Boret, S., Montusclat, S., Margain, A., Pruvost, S., Nicolson, S.T., Yau, K.H.K., Revil, N., Gloria, D., Dutartre, D., Voinigescu, S.P., Chantre, A. (2009). 0.13 μ m SiGe BiCMOS Technology Fully Dedicated to mm-Wave Applications. *IEEE Journal of Solid-State Circuits*, 44(9), 2312 – 2321.
3. Badgwell, T. A., Trachtenberg, I., & Edgar, T. F. (1994). Modeling the wafer temperature profile in a multiwafer LPCVD furnace. *Journal of the Electrochemical Society*, 141, 161-172.
4. Biela, J., Schweizer, M., Waffler, S., Kolar, J.W. (2011). SiC versus Si—Evaluation of Potentials for Performance Improvement of Inverter and DC–DC Converter Systems by SiC Power Semiconductors. *IEEE Transactions on Industrial Electronics*, 58(7), 2872 – 2882.
5. Carroll, A., & Heiser, G. (2010). An analysis of power consumption in a smartphone. Paper presented at the Proceedings of the 2010 USENIX conference on USENIX annual technical conference.
6. Chen, C.Y., Chang, K.C., Wang, G.B. (2013a). Study of High-tech Process Furnace using Inherently Safer Design Strategies (I) Temperature Distribution Model and Process Effect. *Journal of Loss Prevention in the Process Industries*, 26(6), 1198–1211.
7. Chen, C.Y., Chang, K.C., Lu, C.C., Wang, G.B. (2013b). Study of high-tech process furnace using inherently safer design strategies (II) Deposited film thickness model. *Journal of Loss Prevention in the Process Industries*, 26, 225-235.
8. Chen, C.Y., Chang, K.C., Huang, C.H., Lu, C.C. (2014). Study of chemical supply system of high-tech process using inherently safer design strategies in Taiwan. *Journal of Loss Prevention in the Process Industries*, 29, 72-84.
9. Chen, S.L., Lu, P.T., Lee, H.L., Lu, C.H., Yuan, S.Y., Tsai, H.Y., Chen, J.R. (2013). Risk Management and Regulatory Control of Toxic Chemicals in Taiwan. *Journal of CHEMICAL ENGINEERING TRANSACTIONS*, 31, 537-542.
10. Desu, S. B. (1989). Decomposition chemistry of Tetraethoxysilane. *Journal of the American Ceramic Society*, 72(9), 1615.
11. Federico, F., Hugh, J.B., Xiao, J., Chen, D.M., Fleetwood, Gonella, L., McLain, M., Schrimpf, R.D. (2008). Total ionizing dose effects in shallow trench isolation oxides. *Journal of Microelectronics Reliability*, 48(7), 1000–1007.
12. Harbeke, G., Krausbauer, L., Steigmeier, E.F., Widmer, A.E., Kappert, H.F., Neugebauer, G. (1984). Growth and Physical Properties of LPCVD Polycrystalline Silicon Films. *Journal of the electrochemical society*, 131(3), 675-682.
13. He, Q., Qin, S. J., & Anthony, J. T. (2003). Computationally efficient modeling of wafer temperatures in a low-pressure chemical vapor deposition furnace. *IEEE Transactions on Semiconductor Manufacturing*, 16, 342-350.

14. Hendershot, D.C. (1997). Safety through Design in The Chemical Process Industry: Inherently Safer Process Design. Benchmarks for World Class Safety through Design Symposium.
15. Huang, H.P., Jeng, J.C., Chiang, C.H., Pan, W. (2003). A direct method for multi-loop PI/PID controller design. *Journal of Process Control*, 13(8), 769–786.
16. Jensen, K. F., & Graves, D. B. (1983). Modeling and analysis of low pressure CVD reactors. *Journal of the Electrochemical Society*, 130, 1950-1957.
17. Khakzad, N., Khakzad, S., Khan, F. (2014). Probabilistic risk assessment of major accidents: application to offshore blowouts in the Gulf of Mexico. *Journal of Natural Hazards*, 74(3), 1759-1771.
18. Khan, F. I., & Amyotte, P. (2004). Integrated inherent safety index (I2SI): a tool for inherent safety evaluation. *Journal of Process Safety Progress*, 23(2), 136-148.
19. Kim, I. K., & Kim, W. S. (1999). Theoretical analysis of wafer temperature dynamics in a low pressure chemical vapor deposition reactor. *International Journal of Heat and Mass Transfer*, 42, 4131-4142.
20. Kirousis, L.M., Kranakis, E., Krizanc, D., Pelc, A. (2000). Power consumption in packet radio networks. *Journal of Theoretical Computer Science*, 243(1-2), 289–305.
21. Kletz, T. A. & Amyotte, P (2012). *Process Plants: A Handbook for Inherently Safer Design*, Second Edition. Taylor & Francis.
22. Kocher, P., Jaffe, J. and Jun, B. (1999). Differential power analysis, *Proceedings of Advances in Cryptology*, 388-397.
23. Liao, L., Lin, Y.C., Bao, M.Q., Cheng, R., Bai, J.W., Liu, Y., Qu, Y.Q., Wang, K.L., Huang, Y., Duan, X.F. (2010). High-speed graphene transistors with a self-aligned nanowire gate. *Journal of Nature*, 467, 305–308.
24. Lin, Y.C., Yang, C. (2002). Risk assessment in safety management of the semiconductor industry in Taiwan. *Journal of Risk Assessment and Management*, 3(2-4), 222-233.
25. Shnayder, V., Hempstead, M., Chen, B., Werner, G.A., Welsh, M. (2004). Simulating the power consumption of large-scale sensor network applications, *International Conference on Embedded Networked Sensor Systems*, 188–200.
26. Stutzmann, N., Friend, R.H., Sirringhaus, H. (2003). Self-Aligned, Vertical-Channel, Polymer Field-Effect Transistors. *Journal of Science*, 299(5614), 1881-1884.
27. Sze, S. M., & Ng, K. K. (2006). *Physics of semiconductor devices* (3rd ed.). Wiley, ISBN 978-0-471-14323-9.
28. Zhou, J.F. (2010). SPA–fuzzy method based real-time risk assessment for major hazard installations storing flammable gas. *Journal of Safety Science*, 48(6), 819–822.

(a) Structure of 12 "LPCVD furnace tool (b) Commercialized 12 "LPCVD furnace tool settings

Figure 1 The High-Tech process machine of 12 "LPCVD furnace

Figure 2 Timing Diagram of heating and depositing process of furnace, wafer, and reaction gas

Figure 3 Advanced LogicProduct Architecture of 22nm IC

Figure 4 temperature control framework of LPCVD five heating zones

Figure 5 SCR (Silicon Controlled Rectifiers) power control architecture of power supply for heating zone

Figure 6SCR powercontrol at input60% power Consumption

Figure 7temperature control circuit of 12"experimental testfurnace

Figure 8 simulation and experiment results of non-process wafers

Figure 9 relations of reaction rate and temperature of TEOS

Figure 10 simulation and experimental results of first lot

Figure 11 simulation and experimental results of second lot

Figure 12 the SEM thin film checking after process about 5009Å

Figure 13 Detailed control profile of one heating zone temperature

(a) Normal situation

(b) Infrared detecting image

Figure 14 Infrared detecting for 12" furnace

(a) thermal process area in clean room (b) tool piping in sub-fab

(c) terminals burning of heating zone

Figure 15 Commercial manufacturing plant environment and energy hazards

Figure 16 Inherently safer design application strategy in chemical process and plant

Table 1 Summary of the importance changes in advanced 22nm IC processes

Device structure	Position of importance changes	Property change of Materials	Safety refocused of process change	Analysis of Safety and health management issues
Metal Gate		Replace polysilicon gate adopted to reduce gate resistance.	Raw material changed from explosions (Silane) to metal vapor.	This change is more safety than before process condition, but the new process will increase the metal exhaust pollutants.
Channels of Source and Drain		Enhanced the mobility of electrons and holes, and then improved the speed of the device.	Using epitaxial growth to produce a silicon germanium (SiGe) and silicon carbide (SiC).	Increased the process safety management complexity caused by in addition to the original ion implantation process, but also adding epitaxial process.
Technology of self-aligned Copper non-electroplating		The covering copper surface technology for using in after CMP (Chemical Mechanical Polishing, CMP) process.	Prevented the diffusion of copper then reduced electro migration, and then improved the reliability of the copper wire connection.	Increased process steps, and chemicals usage, then hazardous waste will be raised.

<p>Hardmasklayer of Metal(TiN)</p>		<p>For used in the low-k dielectric etch Mask layer.</p>	<p>ImprovedMask layerhardnessto ensure a low-kdielectric etchesquality.</p>	<p>The hazardous no difference after process reactive materials change.</p>
<p>Immersion lithography technology of 193nm</p>		<p>Increased to use ofDI waterin photolithography process then reached effect of immersion.</p>	<p>Immersion effectivelymakes lithographyresol utionto continue andremain at22nm.</p>	<p>Process machinebecomes more complex,maintenance personnelwill be increaseoperating time, and then increased the chance ofcontact withhazardousmaterial.</p>
<p>Lead-free solder</p>		<p>Reducedto use the lead solder.</p>	<p>Due to technicalupgrading, usingthe lead-freesoldercan continue toreachthe weldingpurposes .</p>	<p>Reducingleadfu megeneratedopportunities, and thenreduced hazard level andsafety upgrade.</p>

Table 2 Analysis hazards in advanced 22nm IC process, equipment, and facility system

process steps	Function and composition of process machines	Analysis of Potential hazards
Block Growth	Agencies, cooling system, pressure gauges, control valves, motors, piping, wiring, monitoring system.	High-Temperature, Gas Leak, Fire, Explosion, Shock, Rolling and Crimping
Wafer Cutting and Polishing	Reactor, display screen, control panel, driving elements, agencies, grinding wheels, wire cutting body, piping, wiring, monitoring system.	Organic Solvent Poisoning, Acid and Alkali corrosion, Shock, Rolling and Crimping, Hitting, Cutting.
Oxidation and Thermal Processing	Wafer transfer system, agencies, Heat dissipation, air filtration, heaters, power supply system, piping, wiring, monitoring system.	High-Temperature, Fire, Explosion, Shock, Rolling and Crimping.
Diffusion	Wafer transfer system, agencies, cooling system, air filtration, heaters, power supply system, piping, wiring, monitoring system.	High-Temperature, Gas Leak, Fire, Explosion, Shock, Rolling and Crimping.
Physical Vapor Deposition, PVD	Wafer transfer system, Reactor, power supply system, Isolation valves, refrigeration valves, mechanical pump, piping, wiring, monitoring system.	High-Temperature, Gas Leak, Fire, Explosion, Shock, Rolling and Crimping.
Chemical Vapor Deposition, CVD	Wafer transfer system, Reactor, controller, gas supply system, vacuum system, grounding, piping, wiring, monitoring system.	High-Temperature, Gas Leak, Acid and Alkali corrosion, Fire, Explosion, Shock, Rolling and Crimping.
Photo Lithography	Wafer transfer system, spin chamber, photoresist (PR) coating, Robot arm, vacuum system, agencies, grounding, rotator, soft baking element, piping, wiring, monitoring system.	High-Temperature, Gas Leak, Acid and Alkali corrosion, Fire, Explosion, Shock, Rolling and Crimping.
Etching	Wafer transfer system, Reactor, Electrode plate, wafer boat, magnet coil, vacuum system, RF generator, gas supply and control system, grounding, cooling water systems, piping, wiring, monitoring system.	High-Temperature, Gas Leak, Acid and Alkali corrosion, Fire, Explosion, Shock, Rolling and Crimping, Radiation.

Ion Implantation	Wafertransfersystem, agencies,ionsource supply system, filter, ion analysis device, 4 pole focusing, electrostatic deflector, scanner, magnetic lens, accelerator, crystalholder,Faraday cup, cryogenic pumps, grounding, cooling water systems,piping, wiring, monitoring system.	High-Temperature,Gas Leak, Acid and Alkali corrosion,Fire,Explosion,Shock, Rolling andCrimping, Radiation.
Chemical MechanicalPolishing, CMP	Wafertransfersystem, polishing apparatus, agencies, polishingchamber, brushing device, piping, wiring,monitoring system.	Gas Leak, Acid and Alkali corrosion,Fire,Explosion,Shock, Rolling andCrimping.
Clean process(Wet Bench)	Wafertransfersystem, cleanchamber,wafer carrier, steam drying system, robot arm, agencies,piping, wiring, monitoring system.	Gas Leak, Acid and Alkali corrosion,Fire,Explosion,Shock, Rolling andCrimping.
Packing process	Waferassembly platform, wafer transfer system, visuallylens group, ejection mechanism, lead frame, lead frametransfer mechanism, gluingmechanism, pick and place mechanism, agencies,piping, wiring, monitoring system.	Gas Leak,High-Temperature, Acid and Alkali corrosion, Fire, Explosion,Shock, Rolling andCrimping, Hitting, Collapsing.
Facility system	Clean rooms, offices, rawmaterial storageroom,channel, chemicals rooms,electricalrooms,ventilation system, piping andracks,outdoorstorage tanks, wastewater treatment facilities.	Gas Leak,High-Temperature, Acid and Alkali corrosion, Fire, Explosion,Shock, Rolling andCrimping, Hitting, Collapsing, Drowning,hypoxia.

Table 3 thethin film materials of CVD process used

Application on IC (Integrated Circuit)	types of Thin Film	Raw Materials
Semiconductor	Si(poly)	SiH ₄ (silane)
	Si(epi)	SiCl ₂ H ₂ (DCS) SiCl ₃ H(TCS) SiCl ₄ (Siltet)
Dielectrics	Silicon oxide	SiH ₄ , O ₂ SiH ₄ , N ₂ O Si(OC ₂ H ₅) ₄ (TEOS), O ₂ TEOS TEOS, O ₃ (ozone)
	Oxynitride	SiH ₄ , N ₂ O, N ₂ , NH ₃ SiH ₄ , N ₂ , NH ₃ SiH ₄ , N ₂ , NH ₃
	Si ₃ H ₄	C ₈ H ₂₂ N ₂ Si(BTBAS)
Conductors	W(tungsten)	WF ₆ (tungsten hexafluoride), SiH ₄ , H ₂
	WSi ₂	WF ₆ (tungsten hexafluoride), SiH ₄ , H ₂
	TiN	Ti[N(CH ₃) ₂] ₄ (TDMAT)

	Ti	TiCl ₄
	Cu	(hfac)Cu(tmv _s)

Table 4 related materials and reactor types of CVD

Types of thin film	materials	reactor types of CVD
Thin film of Dielectric Materials	SiO ₂	AP,LP,PE,HDP
	PSG	AP,PE
	BSG	AP,PE
	BPSG	AP,LP,PE
	Si ₃ N ₄	LP,PE
	SiO _x N _y	PE
	Polysilicon	LP
Thin film of Conductive material	WSi _x	LP
	W	LP
	TiN/Ti	LP,PE(MO)
	Cu	LP,PE(MO)
Thin film of low-k materials	Carbon-doped SiO ₂	PE
	Carbon-doped amorphous silicon	PE
Thin film of high-k materials	Ta ₂ O ₅	LP(MO)
	BST	LP(MO)
PSG: Phosphor Silicate glass BSG: Boron-Silicate glass BPSG: Boron and Phosphor Silicate glass BST: Ba _{0.5} Sr _{0.5} TiO ₃ AP: Atmospheric CVD LP: Low pressure CVD PE: Plasma enhanced CVD HDP: High-density plasma CVD MO: Metal-Organic CVD		

Table 5 conditions of LPCVD reactor in this study

Condition	Unit
Inlet gas flow rate : TEOS	380 sccm
Pressure	0.6 Torr
Tube diameter	435 mm
Wafer diameter	300 mm
Tube length	1215 mm
Rotation rate	2 rpm
Deposition time	24.2 min
Wafer	125wafers
Side Dummy : Top	14 th
Side Dummy : Bottom	6 th
Monitor	3wafers
Capacity	148wafers

Table 6 each heating zone running current of 100 wafers

	Current Value (A)				
Process time	Zone1	Zone2	Zone3	Zone4	Zone5
10min	15.89	16.63	17.71	17.78	0
20min	15.99	17.67	17.79	17.84	0
30min	16.16	17.70	17.80	17.87	0
40min	16.38	17.74	17.81	17.90	0
50min	16.75	17.78	17.84	17.92	0
Average	16.23	17.50	17.79	17.86	0

Table 7 each heating zone running current of 125 wafers

	Current Value (A)				
Process time	Zone1	Zone2	Zone3	Zone4	Zone5
10min	15.87	16.65	17.7	17.77	17.86
20min	15.97	17.67	17.81	17.85	17.99
30min	16.18	17.73	17.83	17.89	18.07
40min	16.35	17.77	17.89	17.92	18.15
50min	16.78	17.8	17.95	17.95	18.21
Average	16.23	17.52	17.83	17.87	18.05

Table 8FMEAanalysis results of temperature control system for12” furnace tools

Name of parts (Part No.)	Failure mode	Cause of failure	Method of cognitive failure	Effect	Seve- rity	Like- lihood	Protective equipment	Remarks or description
Element control panel (HZ-001)	The control circuit board failure	1.Electronic Components burned 2.Open or short circuit 3.Control operation interface failure	1.Inoperable and uncontrolled temperature 2.Scorch smell	1. Overheat and catch fire 2.Defective products 3.Process no action 4.Unable to control process tool power consumption	3	0.0002	Yes	System circuit breaker protection and warning light
Temperatur e display (HZ-002)	Display and circuit failure	1. Display board failure 2. Open or short circuit	1. Operating temperature cannot be displayed or display is unstable 2.Scorch smell	1. The actual temperature value is unknown 2. Defective products	2	0.001	No	Available to use infrared temperature equipment to get the actual temperature
Digital process controller (HZ-003)	The control circuit board failure	1.Electronic Components burned 2.Open or short circuit 3.Digital computing interference	1.Process stops functioning andwarning lighting 2.Scorch smell	Process stops functioning	1	0.001	Yes	The reaction gases linked and stopped supply and process automatically
Power supply unit (HZ-004)	The control circuit board failure	1.Electronic Components burned 2.Open or short circuit	1.Unable to control fiveheating zone 2. Scorch smell	1. Overheat and catch fire 2.Defective products	3	0.003	Yes	Systemcircuit breaker protectionand warning light
Digital temperature controller	The control circuit board	1.Electronic Components burned	1.Process stops functioning andwarning lighting	1. Overheat and catch fire 2.Defective products	3	0.001	Yes	System circuit breaker protectionand

(HZ-005)	failure	2.Open or short circuit 3.Digital computing interference	2.Scorch smell					warning light
Heating element 1~5 (HZ-006)	Heating element failure	1. Heating elements burned 2. Open or short circuit 3. Ohmic contact is too large	1.Process stops functioning andwarning lighting 2. Scorch smell	1. Overheat and catch fire 3.VESDA system action	4	0.07	Yes	1.System circuit breaker protection and warning light 2. VESDA system established
Reactor wall (HZ-007)	Cracking	Subjected to impact to crack	Cannot create a vacuum inside the reactor	No producing	3	0.00004	Yes	Value of vacuum detection system established
Cold junction compensati on box (HZ-008)	Over heat	1.Ohmic contact is too large 2.Insufficient bolt torque	1.Process stops functioning andwarning lighting 2.Scorch smell	1. Overheat and catch fire 2.Defective products 3.VESDA system action	3	0.005		1.System circuit breaker protection and warning light 2. VESDA system established
Thermocouple (HZ-009)	Unable to measure temperature	1.thermocoupleburned 2.Circuit contacts off	1.Process stops functioning andwarning lighting 2.Scorch smell	1.Defective products 2. No producing	3	0.002	Yes	1.Digital temperature control system established 2. VESDA system established
Quartz tube (HZ-010)	Cracking	1.Subjected to impact to crack 2.Temperature changeto crack	1. Machine internal gas leak detection system operation. 2. Process stops functioning	1.Defective products 2.ERT action	4	0.00008	Yes	1. Machine internal gas leak detection system established. 2. The reaction gases linked and stopped supply

Fan unit for fast ramp down (HZ-011)	The control circuit board or fan failure	1.Electronic Components burned 2.Open or short circuit	Cooldown time increased	Each batch process time becomes longer	1	0.01	Yes	1.Digital temperature control system established
<p>Explanation:</p> <ol style="list-style-type: none"> 1. The likelihood were derived from the supplier commercial machine, A-412 in this study.The heating element failure ratestatistics of real plant was consistent with the original maintenance manual(ASM, 2013). 2. Severitybased on SEMI-S10 was divided into five risk levels: thehighestisfive, and the lowest is one. 3. Remarks or description was supplemented by protective equipment provided both programs and possible options, for thereaders' reference. 								