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Standby Power Saving in Mechanical Vacuum Pump Realized by

Implementation of the Sleep Mode

THESIS

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ABSTRACT OF THE THESIS

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Master of Science in Electrical Engineering

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Professor G.P. Li, Chair

Mechanical vacuum pumps are widely used to realize low vacuum environments and are commonly set to operate continuously to maintain a certain standby pressure in vacuum systems. Huge electric power consumption during the standby state could be observed. This thesis presented a method by implementing a mode-switch mechanism to the pump that could achieve 80% standby power saving. This mechanism allows the pump to switch between its normal work mode and a sleep mode, which would shut off the pump's power supply and let the pressure inside the vacuum chamber increase to a threshold above its standby pressure. Once the threshold is reached, the work mode would restore the power supply and pump down the chamber to its standby pressure. A detection module was developed to suspend the mode switching when users are operation the tool. The power-saving results and impacts of sleep mode with different threshold pressure were analyzed in this thesis.

CHAPTER 1. INTRODUCTION

Vacuum systems are widely used in various manufacturing processes, such as semiconductor manufacturing [1]. In the semiconductor industry, vacuum pumps play a crucial role in most processing instruments like chemical vapor deposition (CVD) and reactive ion etching (RIE) by reducing the pressure inside process chambers to prevent contamination and improve uniformities [2]. In many vacuum systems, motor-driven mechanical vacuum pumps are commonly utilized as the main pump to provide a low-vacuum environment or complement other high-vacuum pumps, such as cryopumps and turbomolecular pumps [3]. The widespread application of motor-based mechanical pumps makes their electricity consumption account for 21% of the total industrial electricity consumption [4]. In addition to consumptions caused by depressurization during fabrication processes, the continuous operation of pumps to maintain constant pressure inside the chamber during the standby process also consumes vast electric power. Thus, this thesis proposes a new method by implementing a sleep mode on the mechanical pump to reduce the standby state power consumption.

A well-studied method of standby power savings is using variable speed drive (VSD) to regulate the rotation speed of motors and can achieve 30% to 60% power savings; however, the installation cost of VSDs could be huge [5].

The sleep mode introduced in this thesis is realized by a low-cost relay circuit. With a concept of allowing the pressure inside the process chamber to vary within a certain range above the standby pressure in the machine's idle state, the proposed method would shut off the mechanical pump until the chamber pressure reaches a pre-set threshold. Then a pump-down cycle will be performed to reduce the pressure to standby parameters. An overall 80% of power-saving can be achieved during the standby state. An interaction detection function is also implemented to ensure that the user's operation will not be interrupted. The potential impacts of sleep mode on the process performance and pump's work conditions are characterized in this thesis.

The proposed method was tested on the Plasma-Therm 790 system. It is a dual-chamber system with Reactive Ion Etching (RIE) and Plasma Enhanced Chemical Vapor Deposition (PECVD) capabilities. The machine utilizes a rotary vane mechanical vacuum pump to realize millitorr-range pressure in process chambers. The pump is connected to two chambers through a vacuum valve, and a throttle valve at each chamber is used to regulate the pressure. Based on the user's selection, one of the chambers would be activated and maintains at standby pressure in the machine's idle state, the throttle valve at the other chamber would close completely to isolate the inactivated chamber from the pump. A mechanism was developed to identify the activated chamber.

CHAPTER 2. SYSTEM IMPLEMENTATION

The proposed standby-power saving mechanism is realized by a control circuit and a Raspberry Pi running a Python program.

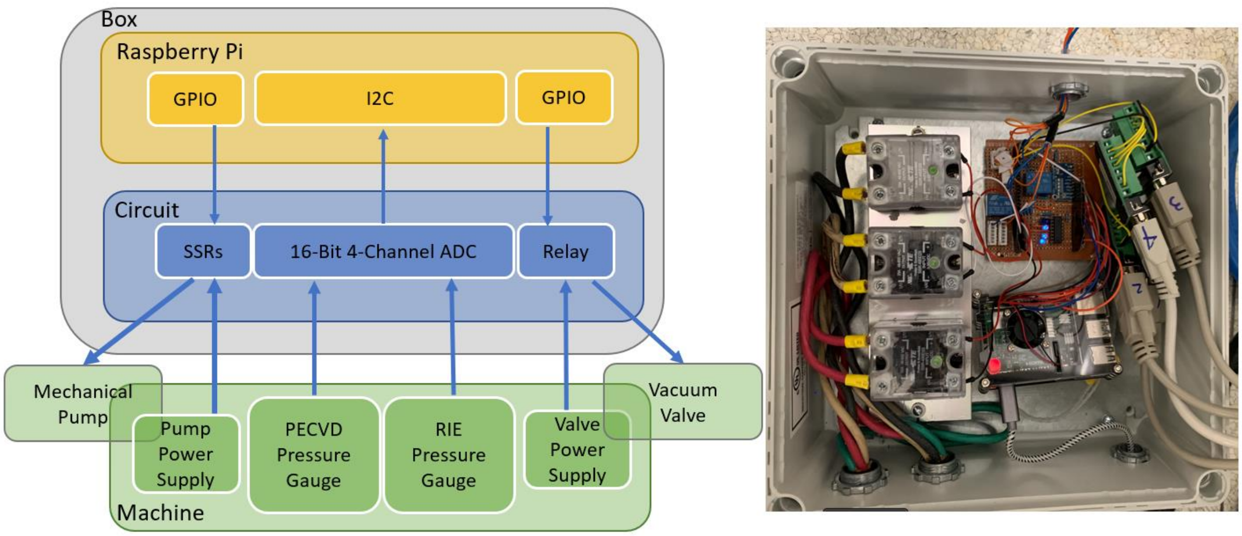


Figure 2.1: a) System architecture. b) Circuit box.

All the components are placed inside an insulated box (Figure 2.1b) and attached to the target machine. The system provides abilities to control the on/off states of the mechanical pump and vacuum valve through relays and parallel read chambers' pressure from the machine's pressure gauges. The details of the software and circuit design will be discussed in the following subsections.

2.1 Software System

A Python program is developed specifically for the target machine, which integrates the following functions: reading pressure value, identifying the activated chamber and define wake-up pressure, selecting work/sleep modes, and keeping the machine in work mode when any interaction is detected.

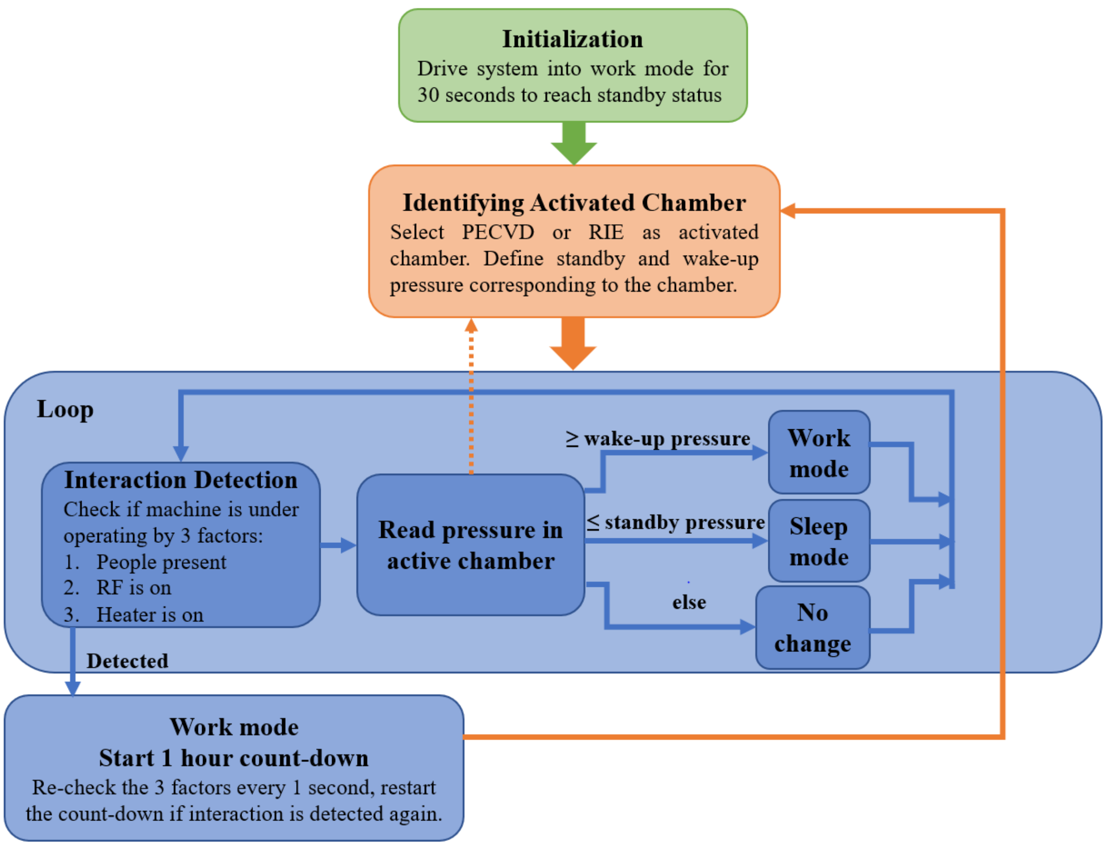


Figure 2.2: Program flowchart

2.1.1 Sleep Mode

When the machine is not operated by users and reaches the standby pressure, the software will switch it to sleep mode by closing the vacuum valve and turning off the mechanical pump in sequence. The activated chamber would leak and outgas until the pressure increases to the pre-set wake-up limit and switch back to the work mode. Zero power consumption of the pump could be achieved during the sleep mode.

2.1.2 Work Mode

The machine's PLC has complete control over the mechanical pump and vacuum valve to guarantee its standard functionality in conducting the deposition and etching process in the work mode. If the machine was previously in sleep mode and reaches the wake-up pressure, the system will switch it to the work mode and perform a pumping-down process until the chamber reaches the standby pressure.

2.1.3 Initialization

After installing the box and running the program, the software will first apply the initialization step by keeping the machine in work mode for 30 seconds to reach the standby condition. Thus, standardized pressure readings are available for identifying the activated chamber in the following process.

2.1.4 Identifying Activated Chamber

Due to PlasmaTherm 790's dual-chamber structure, identifying the activated chamber is necessary for the software to use the correct pressure reading as the criterion in the mode selection. After the initialization, the pressure inside the activated chamber maintains a standby value (9 millitorrs for the RIE or 13 millitorrs for the PECVD). In contrast, the inactivated chamber has a relatively higher pressure reading according to the chambers' physical connection discussed in chapter 1. Thus, the software can use the lower reading within two pressure gauges as an indicator of the activated chamber. The wake-up pressure could be defined depending on the different leakage and outgassing rates between the two chambers and the preferred duty cycle.

Considering the scenario that users change the activated chamber during the operation, the same identifying method would be applied each time the machine quits the work mode to ensure that the activated chamber is updated and the system uses the appropriate threshold value for the mode selection.

2.1.5 Interaction Detection

An interaction detection module is involved in preventing the machine from turning into sleep mode and interrupt precessing during users' operation. The module with a camera and two power meters is able to monitor the states of the RF component, the state of the heater component, and whether people are present at the machine. The system would check these three factors at the beginning of each cycle and force the machine into work mode with a one-hour count down if any factor is detected. During the count down, the system would repeat the detection over these three factors every second and reset the timer once triggered again.

2.2 Control Circuit

The control circuit consists of three sections: the pump control, the vacuum valve control, and the pressure gauge reading. The circuit structure is shown in figure 2.3. All relays for the pump control and valve control are powered by the Raspberry Pi's 5V power supply.

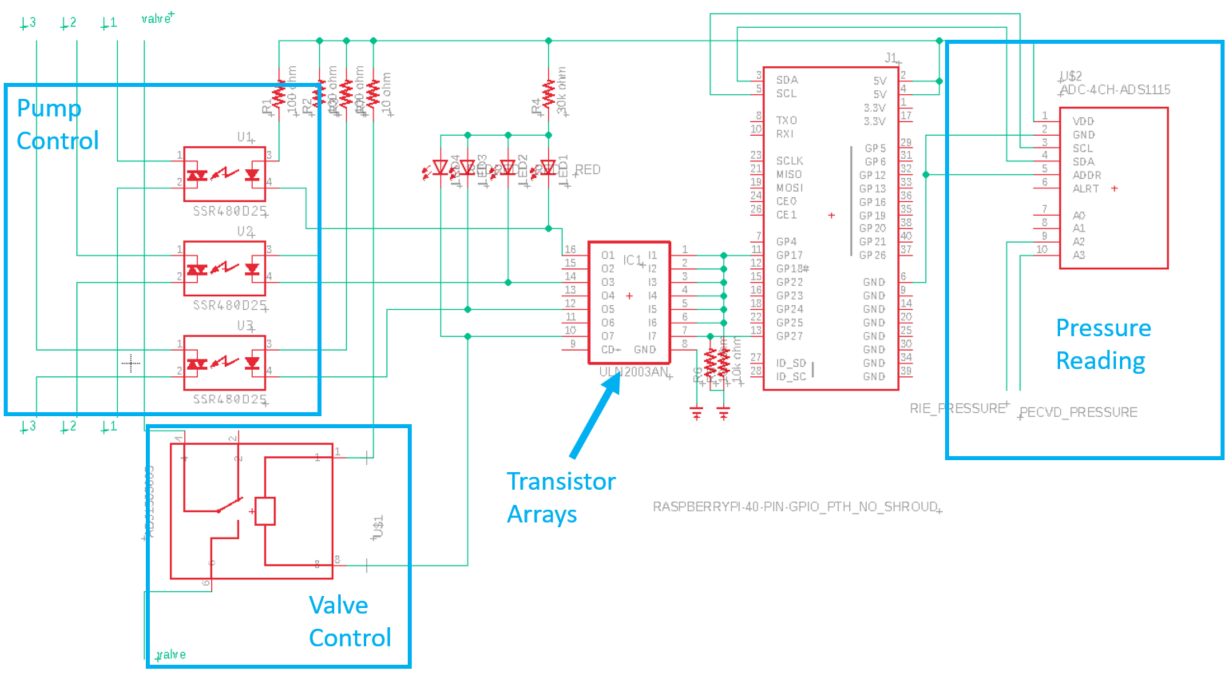


Figure 2.3: Circuit Schematic

2.2.1 Pump Control

The Plasmatherm 790 utilizes a 3-phase 208 volts mechanical pump to provide the ability to reach low-vacuum. In order to control the power supply of the mechanical pump to achieve the purpose of switching modes, three SSRs with the zero-cross feature are used in the presented system.

When designing the control circuit, SSR was selected due to its compact size and short response time. Most important, its small turn-on voltage well satisfies the Raspberry Pi's 5V voltage supply limit. These SSRs are fixed on a $50 \times 70 \times 200$ mm^3 heat sink to meet the need for heat dissipation.

2.2.2 Vacuum Valve Control

A 12V, 0.5W vacuum valve controls the connection between the pump and chambers. When the system switches to the sleep mode, a coil relay soldered on the circuit board can cut off the valve's power to close the valve and isolate chambers from the pump.

2.2.3 Pressure Gauges Reading

There is one pressure gauge in each chamber transmitting the analog pressure reading to the PLC. In order to make the pressure value processable by the Raspberry Pi for mode selection, a 16-bit multichannel ADC is utilized to read two measurements in parallel and deliver the digital output to the processor through the I2C port.

CHAPTER 3. RESULT AND DISCUSSION

3.1 Result of Standby Power Savings

In order to characterize the standby-power savings accomplished by the proposed sleep mode, three different wake-up pressures were set to achieve different duty cycles on the mechanical pump. Under each different pressure setting, the system ran continuously for 24 hours, and five cycles without user interaction were used to represent the standby power consumption. A power meter with a 1/second sampling rate was used to monitor and compare the pump's power before and after sleep mode was implemented.

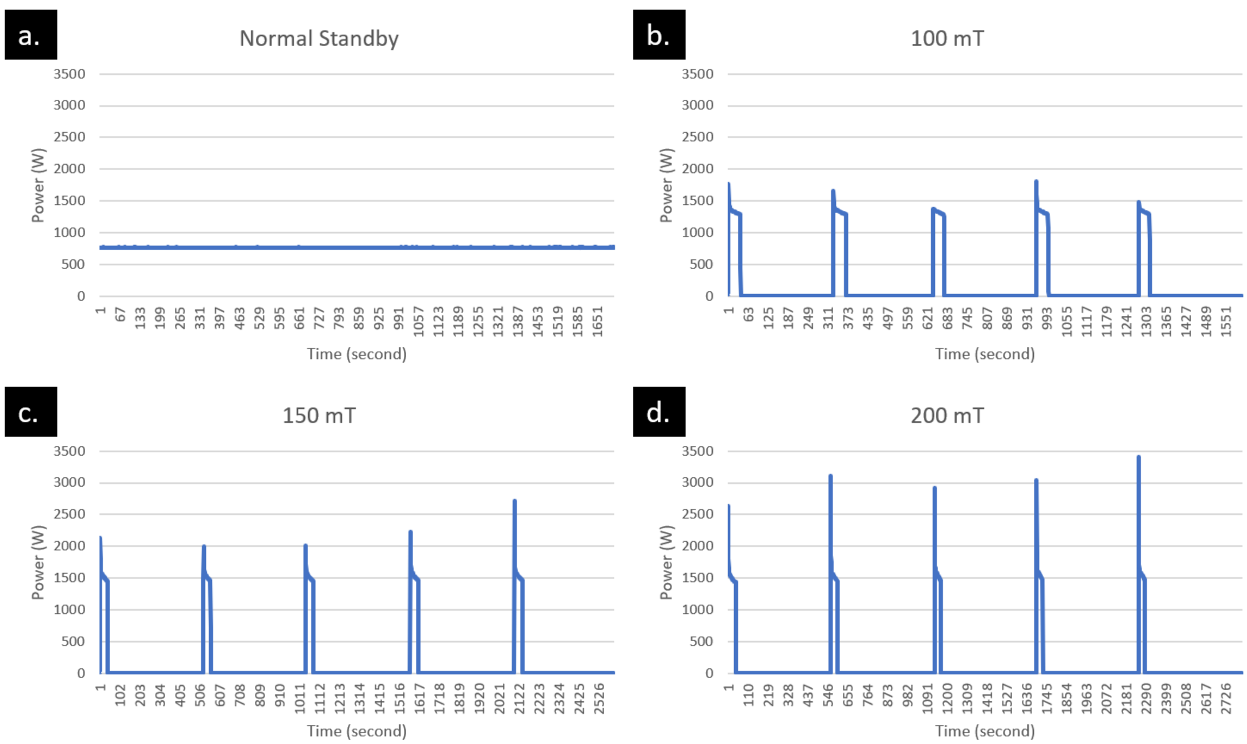


Figure 3.1: Mechanical pump's power with a) normal standby mode. b) sleep mode and a wake-up pressure set to 100 millitorrs c) 150 millitorrs d) 200 millitorrs

Without sleep mode involved, the average power for the pump to maintain the standby pressure is 766.3 watts (Figure 3.1a). After sleep mode was put into use with a 100 millitorrs threshold (Figure 3.1b), the pump would typically work for 37.8 seconds to achieve standby pressure inside the chamber, then sleep for 282.8 seconds until the pressure reaches 100 millitorrs. Due to the repeated switching between work and sleep modes during the standby state of the machine, the system could achieve an 11.79% duty cycle on the pump, with a 153.4 watts average standby power. When the wake-up pressure was set to 150 millitorrs (Figure 3.1c), the average pump-down and sleep period would increase to 40 seconds and 480.6 seconds, respectively, which resulted in a duty cycle of 7.68% and an average standby power of 117.0 watts. As the wake-up pressure further increased to 200 millitorrs (Figure 3.1d), the duty cycle and average standby power decreased to 6.53% and 102.1 watts, respectively. Data of duty cycle, average standby power, and percentage of power-saving are presented in table 3.1.

Wake-up Pressure	Duty Cycle	Average Standby Power (W)	Standby power saving
No sleep mode	100%	766.3	N/A
100 millitorrs	11.79%	153.4	79.98%
150 millitorrs	7.68%	117.0	84.73%
200 millitorrs	6.53%	102.1	86.68%

Table 3.1: Standby power and duty cycle at different wake-up pressure

A higher threshold pressure would significantly extend the sleep period. However, the longer leak and outgas time would also increase the volume of gas and water vapor accumulated inside the chamber, which causes the power and time request for the following pump-down process to increase [6]. From measurements, with a 100 millitorrs wake-up pressure, the average power during the pump-down process is 1308.1 watts. When the threshold was set to 150 millitorrs and 200 millitorrs, the power increased to 1522.5 watts and 1563.0 watts, respectively. The pump-down power and time changes would shrink the further power savings realized by higher wake-up pressures. The mechanical pump's oil condition is also a critical factor that causes the pump-down power and power surge to increase, which will be discussed in section 3.4.

3.2 The Test of Interaction Detection Module

While realizing energy savings, it is necessary to ensure that the instrument can perform RIE and PECVD processes normally. Thus, a test under actual operation scenarios was conducted to evaluate the capability of the interaction detection module.

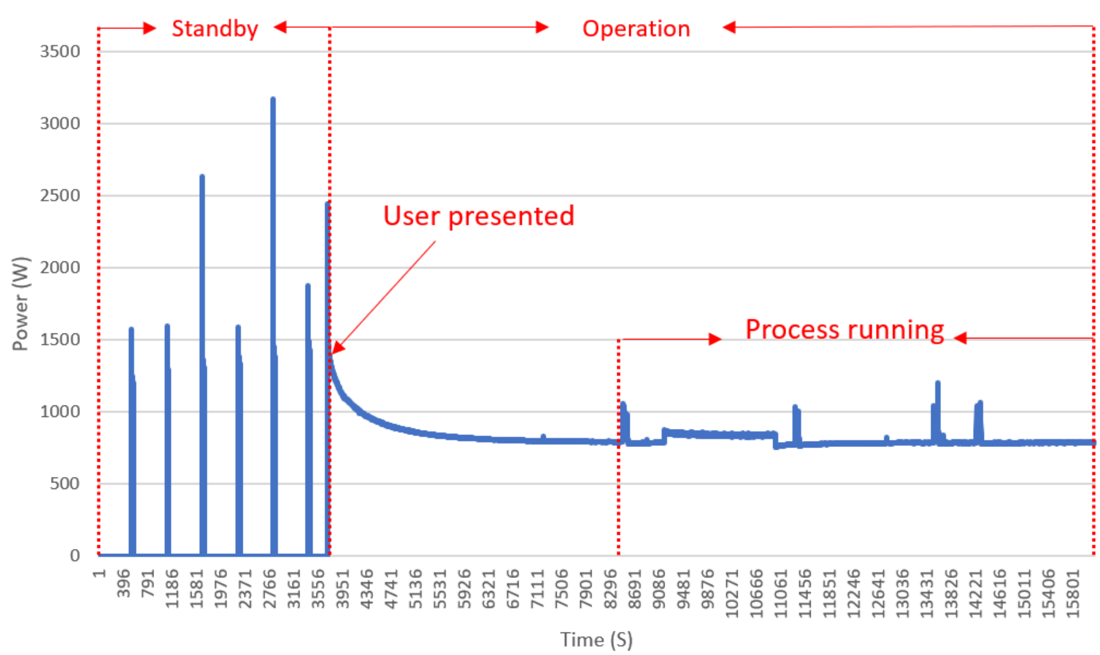


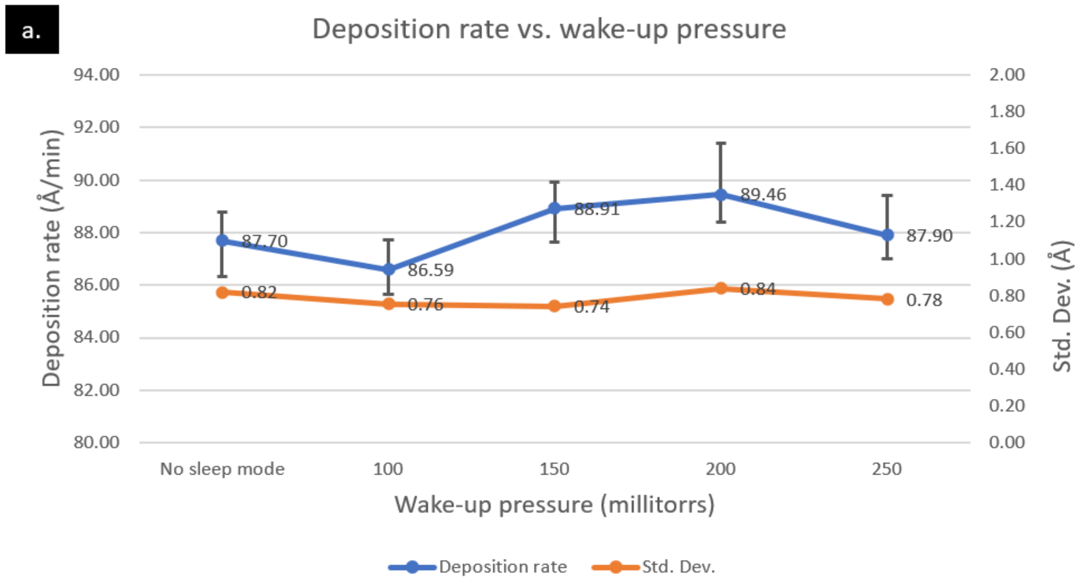
Figure 3.2: Conduct operations with sleep mode implemented

A pump's power plot (Figure 3.2) was generated by the power meter, which shows the state changes of the pump when users started operating. The system would switch between work mode and sleep mode during the standby state as proposed to achieve power savings. When the user presented at the machine, the interaction detection module forced the system into work mode to prepare for the operation. The following fluctuations represent the pump's actions during sample loading and unloading, pressure regulation, and evacuation as recipes specified. Because the system would turn all relays on to restore the pump's power supply in work mode, desired in-process pressures could be guaranteed under PLC's control.

3.3 The Potential Impact of Sleep Mode on The RIE and PECVD Performances

In order to evaluate the sleep mode's potential impact on the RIE and PECVD performance of the machine, nitride deposition and etching were conducted before and after the implementation of sleep mode. Any variation in the deposition rate, deposition non-uniformity, etching rate, and etching non-uniformity could be resulting from the impact of sleep mode and indicate the degradation of performance. The consistent deposition and etching recipes were used for the test.

At each wake-up pressure, a 30-minutes deposition process was first used to grow nitride films on the 4-inch silicon wafer, and Filmetrics F40-NSR was used to measure thicknesses at 9 points to calculate the deposition rate. Then a 1-minute CF_4/O_2 etching was performed, followed by the identical measurement method.



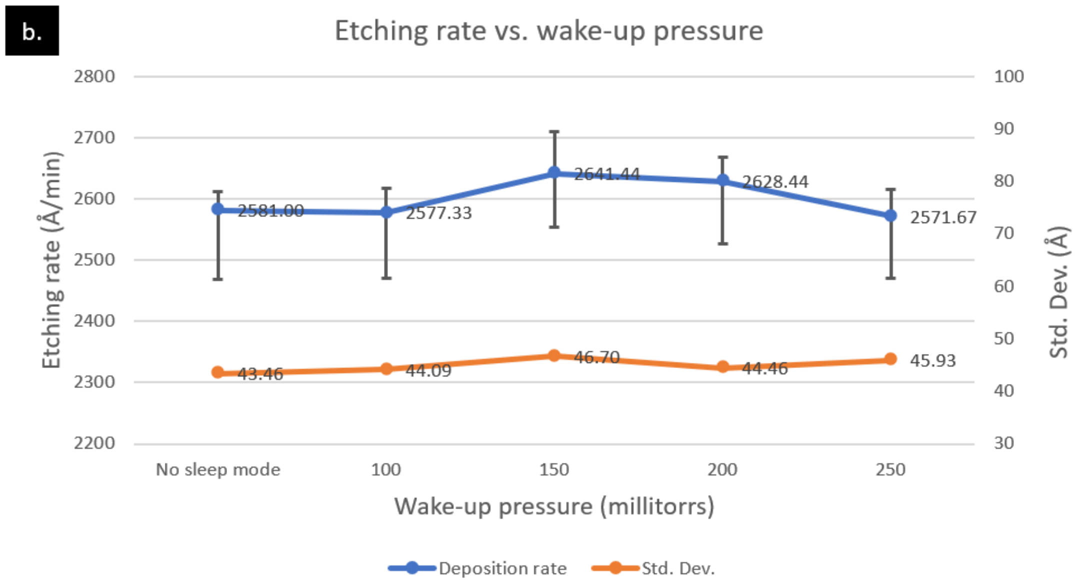


Figure 3.3: Deposition and etching rates versus wake-up pressure. a) Deposition rate. b) Etching rate.

Figure 3.3 shows the resultant deposition and etching rates with standard deviations. The blue curves represent the deposition rate and etching rate under different thresholds in figure 3.3a and figure 3.3b, respectively. At each point on the blue curve, the black error bar denotes the maximum and minimum deposition/etching rate on the wafer. Using the measurements before the implementation of sleep mode as a standard, the variation of deposition rate after employed sleep mode is within 2%, and the variation of etching rate is within 2.34%. No significant trend was found on the deposition rate and etching rate as the wake-up pressure increases.

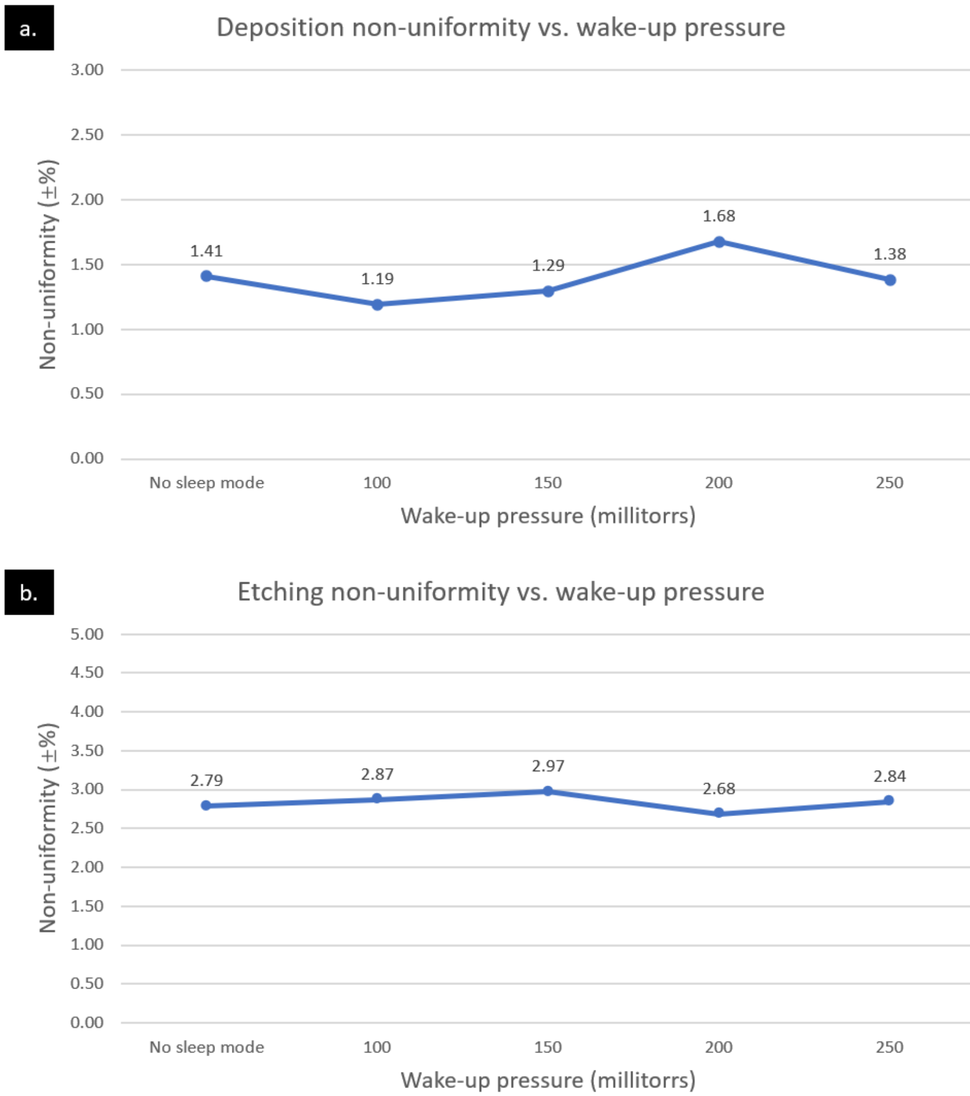


Figure 3.4: Non-uniformity versus wake-up pressure. a) Deposition non-uniformity. b) Etching non-uniformity

Figure 3.4 shows the non-uniformities of deposition and etching processes, which were calculated by:

$$\textit{Non-Uniformity } (\pm\%) = (\textit{Maximum} - \textit{Minimum}) \div (2 \times \textit{Average}) \times 100\% \qquad (3.1)$$

Before and after sleep mode implementation, the nitride film deposition and etching test indicated relative constant performance in deposition rate, etching rate, and their non-uniformities. Moreover, the performance of the instrument showed no obvious variation tendency with the increase in wake-up pressure. Because the proposed power saving method is realized by manipulating the work state of the pump in the standby condition only, a recipe specified in-process pressure could be achieved to ensure consistent process parameters.

3.4 The Potential Impact of Sleep Mode on Mechanical Pump's Working Conditions

Although the sleep mode shows no significant adverse effects on PECVD and RIE performance, its impact on the working condition of the mechanical pump needs to be addressed.

The increase of average pump-down power and time caused by higher wake-up pressure has been discussed in section 3.1. However, because the machine utilizes the oil-lubricated rotary vane mechanical vacuum pump, the changes in oil conditions introduced by sleep mode and their effects on the pump's work condition should also be considered.

When the system switches into sleep mode and turns off the pump, the oil would start cooling down from its normal working temperature, which increases the oil's viscosity and requests more torque from the motor to restart the pump [3]. This mechanism could result in a higher power surge, which can be observed in figure 3.1. In order to characterize the relation between the length of sleep mode and power surge, the peak values captured by the power meter during power surges at different wake-up pressure were compared.

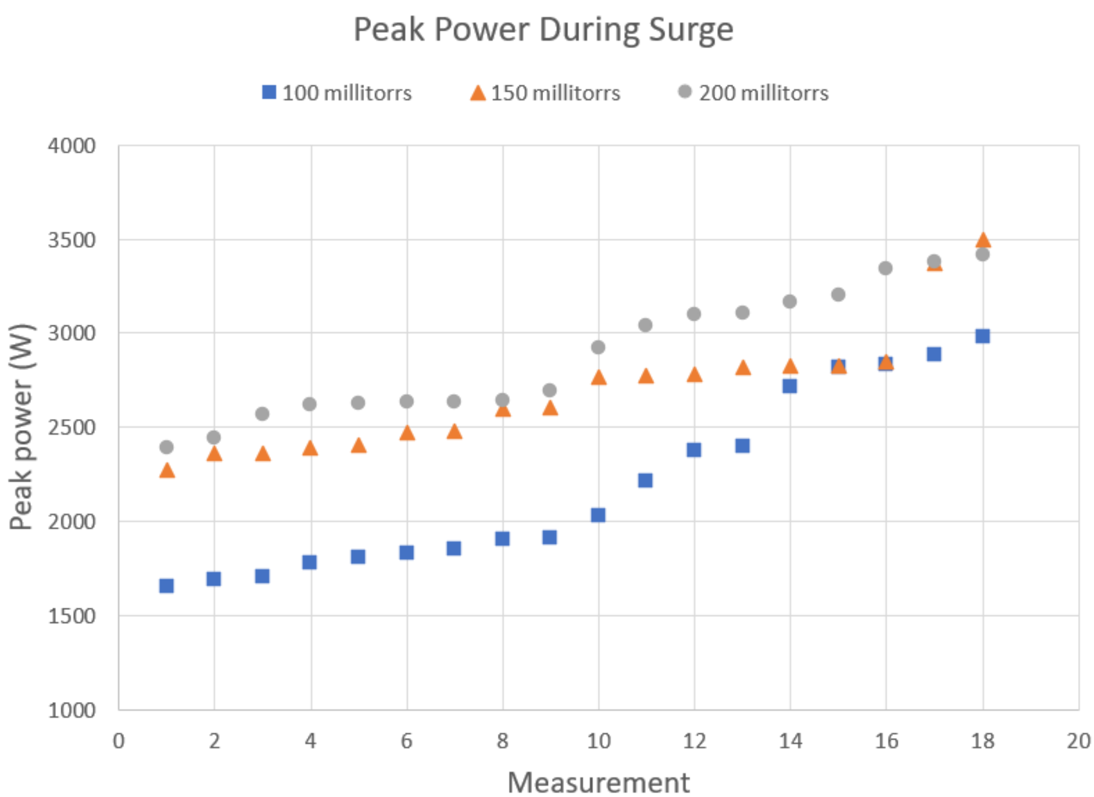


Figure 3.5: Peak power during the power surge under different wake-up pressure

Figure 3.5 presents measurements of peak power when power surges occur. Eighteen measurements were collected under each pressure setting and sorted in ascending order. The blue, orange, and gray marks denote the wake-up pressure at 100 millitorrs, 150 millitorrs, and 200 millitorrs, respectively. An increasing tendency of peak power could be observed as the wake-up pressure rises.

A power surge could be commonly seen in the vacuum system's regular operation, such as pump down from atmospheric pressure. However, an over-high power surge is not desired and might cause severe damage to the equipment without over-power protection. Besides, the oil at lower temperatures with increased friction would also degrade the pump efficiency and lead to higher power consumption during the pump-down cycle. Thus, a longer sleep time of the pump is not always preferred while aiming to save the standby power, and trade-offs need to be taken into consideration when setting the appropriate wake-up pressure.

CHAPTER 4. CONCLUSION

In conclusion, this thesis introduced a low-cost and straightforward method to save standby electricity consumption in the vacuum system by implementing a sleep mode to the mechanical vacuum pump. While a variety of studies have suggested that the variable speed and variable frequency drives could be utilized on the motor-driven vacuum pump for the power saving purpose, this method differentiates itself by achieving zero power consumption during the sleep period.

In sleep mode, the relay circuit cuts off the power supply of the mechanical pump and vacuum valve to permit the pressure inside the chamber to increase to a pre-set threshold. Then the system would switch to work mode by restoring the power of these two components and pump down the chamber to standby pressure. Repeated switching between the two modes keeps the pressure within a certain range while reducing the power consumption in the machine's standby state. An interaction detection module is implemented to suspend the mode switching during the user's operation to guarantee the in-process performance. An 80% of standby power saving was achieved in tests.

The impacts on the process performance and the pump's working condition caused by sleep mode at different wake-up pressure were analyzed in chapter 3, indicated the trade-off that needs to be considered.

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