A STUDY ON THE DESIGN OF A VACUUM AND HEATER FOR FABRICATION OF AMORPHOUS SILICON THIN FILM

Mohd Khairul Hakimin B. Ismail
Bachelor of Electrical Engineering (Hons)
Universiti Teknologi Mara
40450 Shah Alam
E-mail : khairul_isma@yahoo.com

***Abstract* - A compatible vacuum system is vital for the successful operation of and evaporator for material fabrication process. This thesis describes the method of designing a vacuum system well suit for evaporation and deposition of amorphous silicon thin film. Several factors must be taken into consideration in the design of the vacuum so as to match the use. Analysis of the system was conducted before developing real vacuum system is crucial. Vacuum Simulation (VacSim Multi) is PC sofware for simulating vacuum system used in Vacuum Engineering and it was utilised for the purpose of pump selection. This software application can reduce the cost and time of developing the system using hands-on and test-and-build technique. From analysis, it was found out that a combination of Scroll and Turbo pumps or Rotary vane and Turbo pumps are suitable for use in fabricating the amorphous silicon at pressure not less than 10^{-5} torr. However, Rotary vane and Turbo pumps is the best since its pressure delivery is the most stable. The calculation of current supply for heater required at 0.295 A for the duration of 1 hour or 3600 s for evaporation of silicon to take place.**

Keywords : Boat, vacuum pump, evaporator.

I. INTRODUCTION

Vacuum is a pressure lower than atmospheric. Except in outer space, vacuum occurs only in closed system. In the simplest terms, any reduction in atmospheric pressure in a closed system may be called a partial vacuum. It can be achieved by evacuating air from the system.

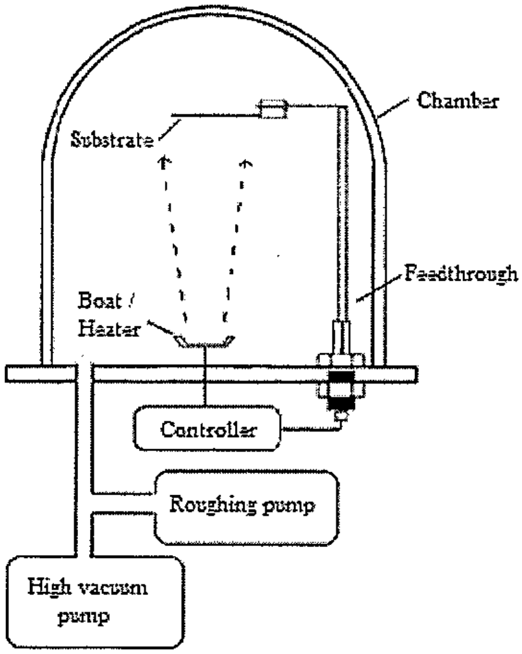

Fig. 1. Vacuum Evaporator System.

Figure (1) shows the vacuum system for material processing. It can be called as thermal evaporator system. The boat hold the evaporant or deposition material and when heated suitably by passing through the current, the material will be evaporated. The evaporation of the material will be condensed onto the substrate. The controller consists of current heating circuit, sensor's circuit and pressure gauge. The compatible roughing pump and high vacuum pump should be employed to attain vacuum environment for desired processing requirement.

II. LITERATURE REVIEW

Deposition Material

The Silicon atom has 14 electrons. It belong to group IV in Periodic Table. The structure of Silicon is crystalline and in diamond cubic crystal. The amorphous silicon can be grown by condensation of Si vapor onto the substrate. One of the method is thermal evaporation techniques whereby the electrical current is supplied to heat the boat and resulting the silicon to melt and evaporate onto the substrate. The crystalline structure of the silicon was disrupted by the heating process and it will grow as an amorphous or non-crystalline structures and denoted as a-Si.

TABLE 1. CHARACTERISTICS OF SILICON

Silicon (Si)	Characteristics
Mass of Wafer (tonne)	500 x 10^{-6}
Melting Point (°C)	1410
Specific heat (J/Kg/C°)	193830
Latent heat of fusion (J/kg)	1926000
Latent heat of evaporation (J/kg)	12800000
Temperature at 10^{-5} torr (°C)	1277

Evaporation Sources

Boat or heater is used as an evaporation source. There are three materials commonly used as evaporation boat.

TABLE 2. CHARACTERISTICS OF THREE COMMON MATERIALS

Material	Melting Point (°C)	Temperature (°C) at 10^{-5} Torr Vapor Pressure
Tungsten (W)	3350	2650
Tantalum (Ta)	3000	2450
Molybdenum (Mo)	2600	2000

Vacuum material

Vacuum material is the vacuum chamber's material. Chamber can be constructed of metal, glass, ceramic, or plastic components. Since all of these materials add to the total gas load in the chamber, selection is critical. Materials that do not bond well with water molecules and do not outgas very fast are ideal.

TABLE 3. MATERIAL'S OUTGASSING RATE [10]

Vacuum Material	Outgassing Rate *(torr liter/sec/cm²)*
Stainless Steel	6×10^{-9}
Aluminum	7×10^{-9}
Mild Steel	5×10^{-6}
High Density Ceramic	3×10^{-6}
Pyrex (Glass)	8×10^{-9}

Metal can be used in ultrahigh vacuum system. At room temperature, few metals have vapor pressure above 10^{-9} torr.

Ceramics are inorganic non-metallic compounds. They have advantages over the glass as a constructional material for insulation application, it is better mechanical strength, particularly at high temperature.

Glass is Silica (SiO_2). A common chamber material in educational and some research laboratories. Glass fulfills many requirements for high and ultra high vacuum.

Gas loads

Gas loads are the gases need to be evacuated from vacuum system. Air contains of several gases. Argon, Helium, Hidrogen and Water are the common major gas loads considered in vacuum system.

There are some causes of gas load exist in the system.

i. **Outgassing**

During the manufacturing process there is gas trapped in the materials. Outgassing is the process whereby the gas embeded or trapped in the materials escape from the materials[2].

ii. **Real leaks**

Path for the molecules to travel from outside chamber to the inside chamber through space in a wall or any connection system can cause real leak to occur[2].

iii. **Permeation**

It acts like a constant leak. It occus in three process. Initially, gas moves to the solid material and the gas adsorbs on the outer wall of the material, then it will diffuses through the material and desorbs from the inner surface[2].

Vacuum Pump

Pump is the primary important to be used to remove gas molecules in the gas phase from a gas-filled volume [12].

Turbo pump The ultimate vacuum of most turbos are between 10^{-7} Torr and 10^{-10} Torr.

Rotary pump have ultimate pressures around 10^{-2} Torr range up to 10^{-4} Torr.

Scroll pump producing an ultimate vacuum in the 10^{-2} Torr range.

III. PROBLEM STATEMENT

The vacuum system is widely used in material fabrication but very least experts and less experiences in developing the system. This project is expected to gain experiences and the basic knowledge in the thermal evaporator system in order to improve the design and for further research in this area.

IV. OBJECTIVE

To study the method of designing the vacuum as thermal evaporator system so that the suitable vacuum system can be design and to identify the current required to supply the heater to enable the evaporation process of Silicon to takes place. The study was done theoretically for the purpose of future study in the area of material processing and vacuum engineering.

V. SCOPE OF WORKS

In this thesis and project, the study only involves the techniques to design a vacuum based on the specified material that is Silicon and also to determine current requirement to evaporate the Silicon. The study did not involve the pressure gauge, sensor and it's circuit. The techniques were most fundamental in order to develop a compatible vacuum system and heating current requirement for the fabrication of amorphous Silicon. This theoretical study to develop techniques for future research and development of real system design and applications.

V. METHODOLOGY

The methodology were represented by the following flow chart:

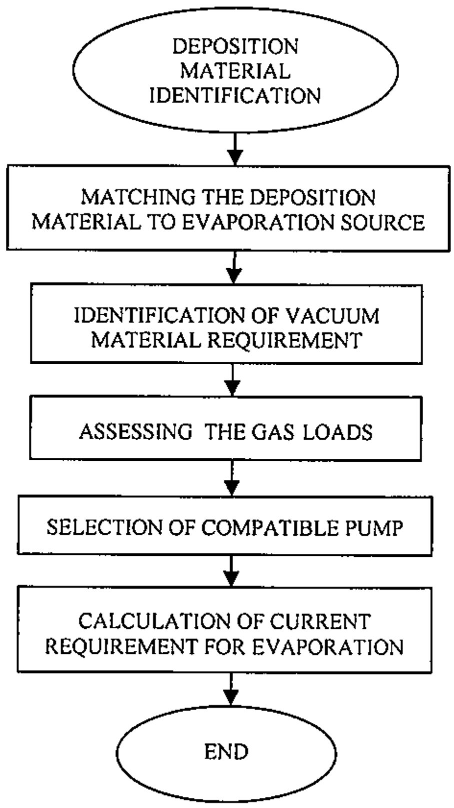

Fig. 2 Flow Chart of Design Procedures

VI. VACUUM AND HEATER DESIGN TECHNIQUES

The process of evaporation was intended to be in vacuum chamber at pressure of 10^{-5} torr or less as usually practiced in material processing and Silicon (Si) was the deposition materials used for fabrication of amorphous Silicon thin film onto substrate.

Pressure of 1 atmosphere (Atm) equal to 760 torr.

A. Deposition material/ evaporant

The Silicon was chosen as the material of the processing to fabricate the amorphous thin film. There are six characteristics of material were required and recorded as follows:

(i) Mass of Wafer (tonne)

(ii) Melting Point (°C)

(iii) Specific heat (J/Kg/C°)

(iv) Latent heat of fusion (J/kg)

(v) Latent heat of evaporation (J/kg)

(vi) Temperature at pressure of 10^{-5} torr (°C)

B. Evaporation Source

Table 2 was taken as a reference for boat selection. Techniques of selecting boat were:

i. Melting point of Silicon and it's vapor pressure at 10^{-5} torr were determined.

ii. The temperature of boat at 10^{-5} torr was identified to be greater than melting point of Silicon at pressure not less than 10^{-5} torr.

iii. Compatible boat was selected based on (ii).

C. Vacuum Material

Vacuum material is the vacuum chamber's material. The materials of the lowest outgassing rate was chosen, it is because to ensure the material to be evaporated free from unwanted gases that might cause impurity to the material.

Another factor was considered are the size of the chosen chamber. Based on the chosen chamber, two factors were determined:

i. Area of chamber

(a) **Area end = $2\pi r^2$** (1)

(b) **Area body = $2\pi rh$** (2)

(c) **Area total = Area end + Area body**

where
r = Radius in cm
h = Height in cm

ii. Thickness of the chamber's material.

From manufacturer data sheet, the chamber's diameter was 25.4 cm with 30.48 cm height and 0.8 cm thickness. The chamber was cylindrical in shape with flat top and bottom.

D. Gas Loads Determination

Gas loads can be assessed by the equation 3.

$$Q_G = Q_D + Q_L + Q_{Per} \quad (3)$$

where

Q_D = Outgassing in torr liters s^{-1}.

Q_L = Leaks torr liters s^{-1}.

Q_{Per} = Permeation torr liters s^{-1}.

$$Q_D = q_D A \text{ (mbar/s)} \quad (4)$$

where

q_D = Specific outgassing rate in mbar liters s^{-1} cm^{-2} of the vacuum material.

A = Total outgassing surface area of chamber in cm^2.

Q_L is Real leaks approximated at 10^{-5} torr liters s^{-1}

$$Q_{Per} = K_{Per} A \Delta_p L^{-1} \quad (5)$$

where

K_{per} = Permeability coefficient of vacuum material.

A = Surface of the material in cm^2.

Δ_p = Pressure gradient across the thickness of the material in atm.

L = Thickness of the chamber's material in cm.

Method of Vacuum Pump Selection

Pump is a means of removing the gas loads. Performance of the vacuum system can be represented as equation 6

$$Q_G = SP \quad (6)$$

The pumping speed of the pump can be obtained from manufacturer's specifications [1],[7].

E. Pump Selection

Pump is the core of the vacuum system. The selection of pump was critical than the previous selection. Pump is means to achieved the desired pressure so that the compatible vacuum system could be attained.

VacSim Multi simulation software was employed for pump selection.

There were five pump simulation tests:

i. Test of Scroll pump
ii. Test of Rotary pump
iii. Test of Turbo pump
iv. Matching Test of Scroll pump with Turbo pump
v. Matching Test of Rotary pump with Turbo pump

Figure 3 was the set-up parameter of the chamber of the vacuum system. It has shown the volume and gases inside the chamber as source of the gas loads.

Figure 4 was the parameter of control timer. The study was not involve setting up the controller. It was included only for the purpose to enable the simulations to be done.

Figure 5 was general parameter of the plotting graphs for the results of pressure achieved by each pump. The atmospheric pressure of air was taken at 760 torr or 1 atm.

General			
User name =	User defined		
Volume	Volume	0.01	Cubic m
Air			
Pressure	Initial Pressure	1	atmosphere
Argon			
Pressure	Initial Pressure	0.0095	atmosphere
Generic			
Pressure	Initial Pressure	0.012	atmosphere
Helium			
Pressure	Initial Pressure	5.1e-06	atmosphere
Hydrogen			
Pressure	Initial Pressure	5.1e-07	atmosphere
Water			
Pressure	Initial Pressure	0.012	atmosphere

Fig. 3. Parameters of Gas Volume

General			
Time	Delay	0	seconds

Fig. 4. Control Timer Parameter

General			
Time	Min. Time	0	seconds
Time	Max. Time	0	seconds
Dimensionless	Time_Log(1)/Linear(0)	0	logic
Dimensionless	Time_AutoScale(1)	1	logic
Pressure	Min. Pressure	1e-10	atmosphere
Pressure	Max. Pressure	1	atmosphere
Dimensionless	Press_Log(1)/Linear(0)		logic
Dimensionless	Press_AutoScale(1)	1	ratio
Dimensionless	Plot_Total	1	ratio
Air			
Dimensionless	Plot_Partial	1	ratio
Argon			
Dimensionless	Plot_Partial	1	ratio
Generic			
Dimensionless	Plot_Partial	1	ratio
Helium			
Dimensionless	Plot_Partial	1	ratio
Hydrogen			
Dimensionless	Plot_Partial	1	ratio
Water			
Dimensionless	Plot_Partial	1	ratio

Fig.5. Graph Ploting Set-up Parameter

i. Test of Scroll pump

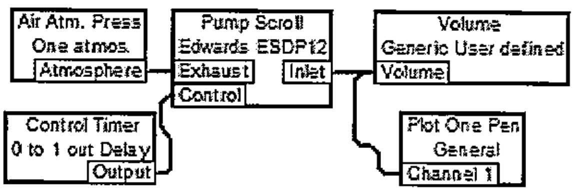

Fig. 6. Configuration of Vacuum System employing Scroll pump.

ii. Test of Rotary pump

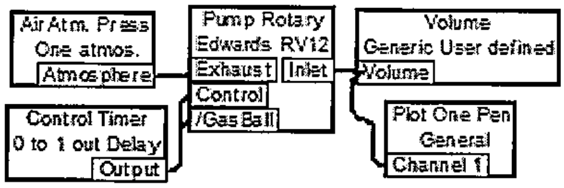

Fig. 7. Configuration of Vacuum System employing Rotary vane pump.

iv. Test of Turbo pump

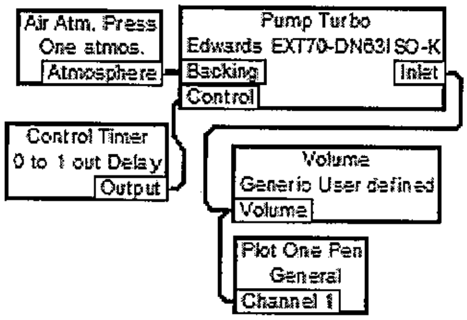

Fig. 8. Configuration of Vacuum System employing Turbo pump.

Figures 6 to 8 show the set up of simulations test of Scroll, Rotary and Turbo pump respectively.

v. Matching Test of Scroll pump with Turbo pump

Figure 9 shows the set up of simulations test using VacSim Multi Software. Scroll and Turbo pump were combine.

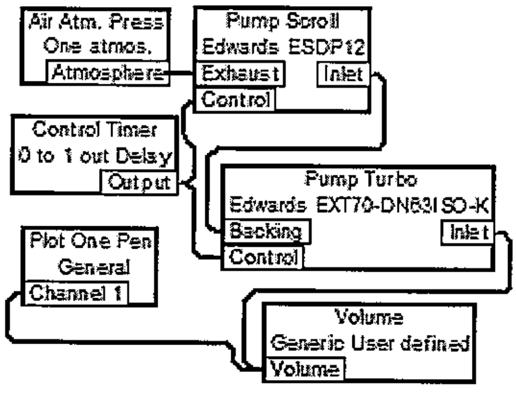

Fig. 9. Configuration of Vacuum System employing Scroll pump and Turbo pump.

The scroll as roughing pump and the Turbo as High vacuum pump.

vi. Matching Test of Rotary Vane pump with Turbo pump

Figure 10 show the set up of simulations test using VacSim Multi Software. Rotary vane and Turbo pump were combine.

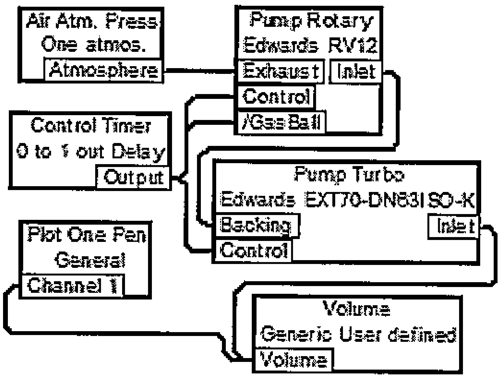

Fig. 10. Configuration of Vacuum System employing Rotary vane pump and Turbo pump.

The Rotary vane as roughing pump and the Turbo as High vacuum pump.

E. Supply Current for Evaporation Process

Supply Current Requirement for evaporation of evaporant (t = 3600 s).

$$E_m = mL_f \quad (7)$$

$$E_v = mL_v \quad (8)$$

$$E_r = mC\Delta T \quad (9)$$

$$E_t = E_m + E_r \quad (10)$$

$$E_t = E_m + E_v \quad (11)$$

$$P_o = \frac{E_t}{t} \quad (12)$$

$$P_o = IV\cos\theta \quad (13)$$

where

E_m	=	Energy for melting in Joule (J)
E_v	=	Energy to raised the temperature from melting temperature to evaporation temperature in Joule
E_r	=	Energy to raised the temperature from initial temperature to melting temperature in Joule
E_t	=	Total of energy in Joule (J)
P_o	=	Input power in Watt
L_f	=	Latent heat of fusion in J/kg
L_v	=	Latent heat of evaporation in J/kg
C	=	Specific heat in J/Kg/C°
ΔT	=	Change in temperature in °C
$\cos\theta$	=	Power factor
t	=	Time in seconds (s)
m	=	Mass in tonnes

VII. RESULTS AND DISCUSSIONS

A. Deposition Material

Silicon was chosen in this study because of Silicon-based semiconductor is widely used in many electronic devices,computer devices and solar cell also harness it's benefits. The some characteristics of Silicon were tabulated in the Table 1.

The mass of the wafer was referred to the manufacturer's catalogue. For this study, the mass of Silicon wafer was taken at 500 g or 500 x 10^{-6} tonnes.

B. Evaporation Source

Based on Table 2, Tungsten boat was chosen as the evaporation source of Silicon. It was because temperature at vapor pressure of 10^{-5} is much higher than the Silicon at the same pressure. It made the process of Silicon evaporation safer without melting the boat instead the Silicon materials. However, in case of unavailability of the Tungsten boat, the choice was Tantalum and followed by Molybdenum . It can be concluded that all these three types of boat were applicable as Silicon evaporation source for the purpose of Silicon evaporation.

C. Vacuum Material

Glass was the vacuum material commonly used for academic purposes. Besides it is transparent, glass also have low outgassing rates which highly required by researcher and experimenter for purity of the processed material. It's transparency enable the process from start to the end of evaporation to be seen by the experimenter.

Area Chamber

- **(i) Area end = 1013.41cm²**
- **(ii) Area body = 2432.1959 cm²**
- **(iii) Area total = 3445.6059 cm²**

Glass fulfills many requirements for high and ultra high vacuum. Many types of glass have low gas permeability and a good vacuum characteristics. These was an advantage of glass despite it more fragile than metal and ceramics.

D. Gas Loads Estimation

The total gas loads estimated are around 460 torr. these are the gases need to be evacuated from the system.

$$Q_D = 3.9969 \times 10^{-6}\ \text{torr.litre.s}^{-1}$$

$$Q_L = 1 \times 10^{-5}\ \text{torr.litre.s}^{-1}$$

$$Q_{per} = 460\ \text{torr.litre.s}^{-1}$$

$$Q_G = 460.000014\ \text{torr.litre.s}^{-1}$$

E. Calculations of Pump Performances

Volume and Initial pressure were 10 liter and 760 torr respectively.

TABLE 5. RESULTS OF FINAL PRESSURE AND TIME TAKEN FOR EACH PUMP BY CALCULATIONS

Pump	Pumping speed (L/s)	Ultimate Pressure (Torr)	Final Pressure (Torr)	Time (s)
Scroll	3.47	1×10^{-2}	132.56	5.03
Rotary vane	1.078	1×10^{-4}	426.71	5.35
Turbo	65	3.7×10^{-5}	7.077	0.719

i. Scroll pump test

Figure 9 shows pressure obtained by employing Scroll pump, at 80 seconds the system had reached the saturation level. From the VacSim simulation result, the total pressure it can achieve was 0.608 torr.

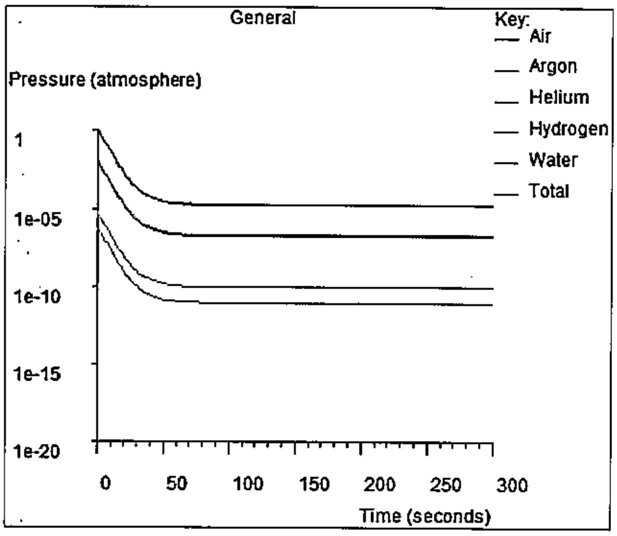

Fig. 9. Pressure obtained by employing Scroll pump.

The Argon, Helium, Hydrogen and water gases also have shown the same rate of reduction each other.

ii. Rotary pump test

Figure 10 shows performance Rotary pump employed on the system. Saturation level at 10^{-4} torr in 40 seconds.

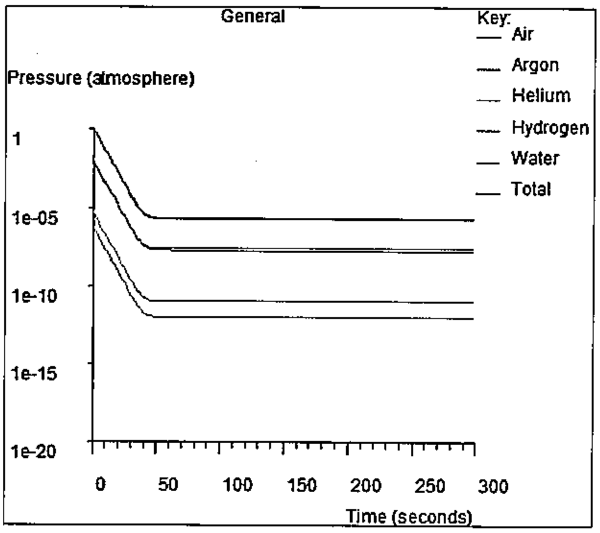

Fig. 10. Pressure obtained by employing Rotary vane pump.

The Argon, Hydrogen, Helium and water gases also have shown the same rate of reduction each other other.

iii. Turbo pump test

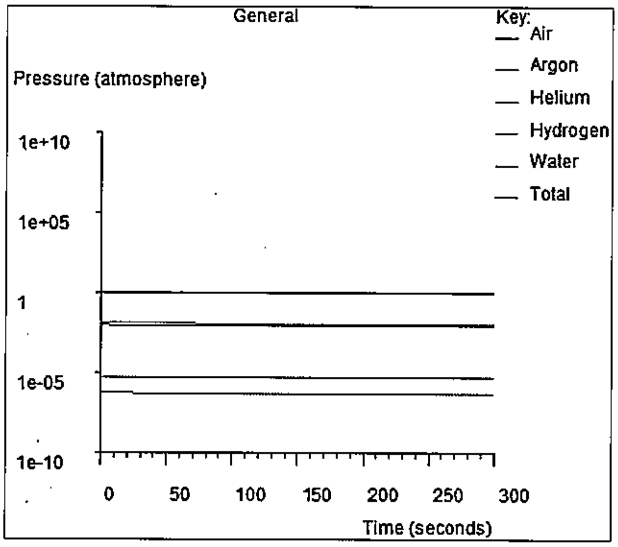

Fig. 11. Pressure obtained by employing Turbo pump.

Figure 11 shows Turbo pump have resulted that the pressure neither reduced nor increased. It keep maintaining the level of the pressure of the chamber. It can be concluded that the Turbo pump would not work as vacuum pump at the initial pressure of 1 atmosphere or 760 torr or above.

iv. Scroll and Turbo pumps test

Figure 12 shows result of combination Scroll and Turbo pump. The simulation had shown the pressure of the system considerably reduced after two minutes of pumping down process up to 10^{-7} atmosphere or 7.6×10^{-5} torr exceeded the requirement of the process. However all gases have not shown the saturation level was attained.

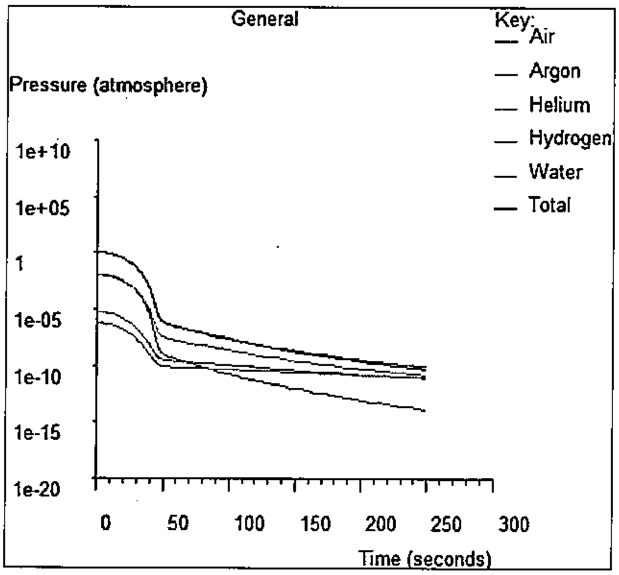

Fig. 12. Pressure obtained by employing Scroll pump with Turbo pump.

v. **Rotary and Turbo pump test**

Figure 13 shows result of combination Rotary vane and Turbo pump. From simulation, the pressure of the system considerably reduced after 40 seconds of pumping down process up to 10^{-12} atmosphere or $7.6x10^{-10}$

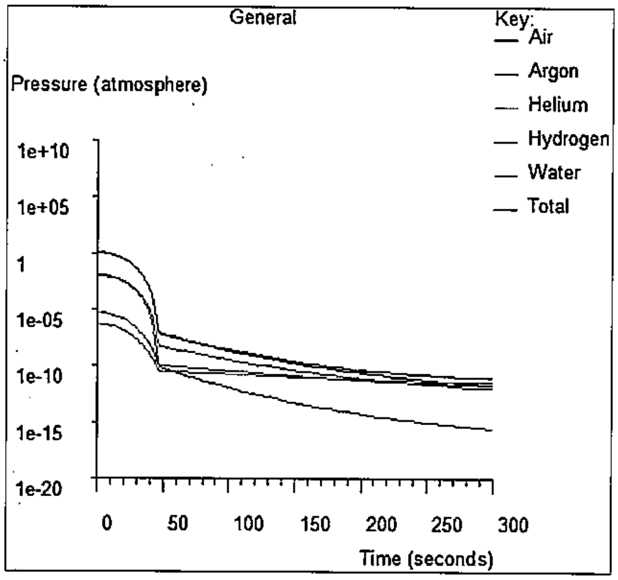

Fig. 13. Pressure obtained by employing Rotary pump with Turbo pump.

TABLE 5. SUMMARIES OF EACH TEST RESULT

Pump	Total Pressure (Torr)	Time (s)
Scroll	0.076	300
Rotary vane	0.0608	300
Turbo	760	300
Scroll+Turbo	7.6×10^{-8}	250
Rotary+Turbo	6.08×10^{-7}	300

From the simulation, the compatible pump for silicon thin film fabrication were combination of Scroll with Turbo, and combination of Rotary with Turbo pump.

It is because, these two combination pumps had attained pressure not less than 10^{-5} torr as required in this process. The best among two are combination of Rotary and Turbo pump.

F. Current Requirement for Evaporation

(a) Current required for melting of Silicon

Equations 7 to equation 13 were applied exception of equation 8 and equation 11.

E_m = 963 J

E_r = 136650.15 J

E_t = 137613.15 J

P_o = 38 Watt

I = 0.144 A

(b) Current required for evaporation of Silicon

The procedures at (a) was followed whereby Equations 7 to equation 13 were applied except equation 7 and equation 10 were unused.

From the above calculations, the current for evaporation was 0.151 A. Thus, total current, It = 0.295 A.

- **Graphical and Numerical Representation of Current Requirement at Fixed Time and Variable Voltage**

Figure 14 shows the current required if there is varying in voltage. The time was fixed at one hour or 3600 s, and the supplied voltage was gradually raised up from 1V to 415V.

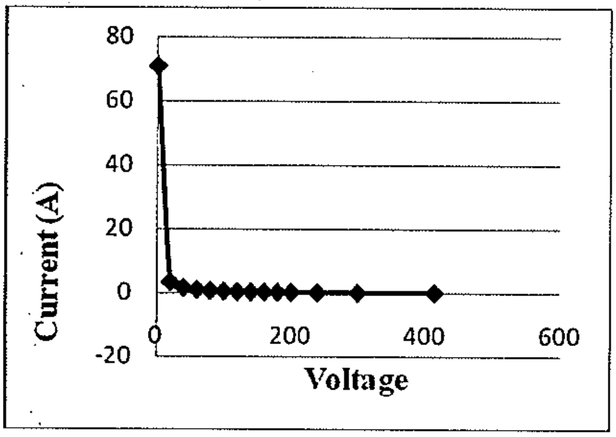

Fig. 14. Graph of Current Requirement with Changing Voltage

- **Graphical and Numerical Representation of Current Requirement at Fixed Voltage and Variable Time**

Figure 5.7 was graphical representation and Table 5.10 was numerical representation that have shown the current required if there is varying in time from 60s to 3600s at fixed voltage of 240V.

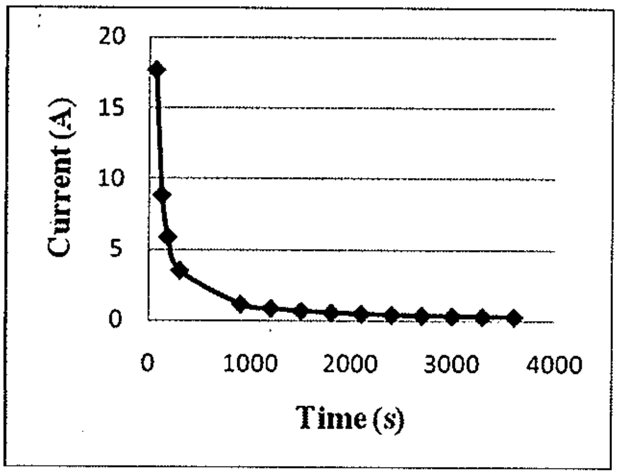

Fig. 15. Graph of Current Requirement with Changing Time

IV. CONCLUSIONS

This study utilised BOC Edward model for pump since the VacSim simulations is most suited since most of the system represented in Edward model. The purpose evaporation was done in high vacuum is to ensure impurities in the growing layer of thin film could be reduced. In this study, combination of Scroll with Turbo pumps, and Rotary vane with Turbo pumps were found to be compatible for the Silicon process in the vacuum. It is because, these two combination pumps had attained pressure not less than 10^{-5} torr as required in this process.The current supply required to evaporate the Silicon for the pressure of 10^{-5} torr in the period of 3600 seconds or one hour is 0.295 A.

REFERENCES

[1] A.Roth, *Vacuum Technology*. New York: North-Holland Publishing Company: 1983.

[2] David M.Hata, *Introduction to Vacuum Technology*. Upper Saddle River, New Jersey Columbus, Ohio: Pearson Prentice Hall, 2008.

[3] G.F Weston, *Ultra High Vacuum Practice*. Great Britain: Butterworth & Co. Ltd, 1985.

[4] David Hucknell, *Vacuum Technology And Applications*. Great Britain: Butterworth-Heinemann Ltd, 1991.

[5] Max Knoll assisted by B. Kazan, *Material and Processes of Electron Devices*. California: Springer-Verlag, 1959.

[6] Armand Berman, *Vacuum Engineering Calculation, Formulas, And Solved Exercises*. Jurusalem: Academic Press, Inc, 1992.

[7] Mary Anne White, *Properties of Materials*. New York: Oxford University Press, 1999.

[8] Phil Danielson, "A Journal of practical and Useful Vacuum Technology," Dec 12, 1991, http://VacuumLab.com

[9] Revised electronic edition, *"Vacuum and Pressure System Handbook,"* Gast Manufacturing, http://www.gastmfg.com/pdf/vphb/vphb_s1.pdf