DESIGN AND CHARACTERIZATION OF SPIN COATER TO SUPPORT NATIONAL SEMICONDUCTOR INDUSTRY

Desain dan Karakterisasi Spin Coater Untuk Mendukung Industri Semikonduktor Nasional

Ardi Rahman[1], Okasatria Novyanto[1], Nurul Alfiyati[1], Ahmad Sidik[2], Irman Idris[2], dan Asep Ridwan Nugraha[3]

[1] National Standardization Agency of Indonesia (BSN), Kompleks Puspiptek Bld. 420, South Tangerang, Indonesia
[2] School of Electrical Engineering and Informatics, Bandung Institute of Technology, Bandung, Indonesia
[3] Research Center for Electronics and Telecommunications, Sangkuriang St., Komplek LIPI Build. 20, Bandung, Indonesia

e-mail: ardi.rahman@bsn.go.id

Abstract

Recently, semiconductor industry grows rapidly due to high demand of modern electronic system. In addition, the value of investments in Indonesia electronic industries also more than doubled during 2015-2017. This increase in investment will certainly have an impact on the increasing the needs for electronic / semiconductor component processing machines. To support it, well performed spin coater then were designed. The characterization of spin coating process was done at BSN (formerly was known as Research Center for Metrology LIPI) using roughness measuring instrument/ profilometer that traceable to PTB (Germany) to guarantee the validity of the measurement results. Characterization experiment used positive photoresist SPR3018 to see the performance of system designed. Three different experiments were performed to determine the impact of spin speed and spin time to photoresist thickness and uniformity. The characterization shown that on spin speed increased, the photoresist was deployed thinner. The thickness of the photoresist is inversely proportional to the square root of spin speed. Furthermore, the longer spin coating time, it increases the tendency of concave surface. This work is expected to benefit the practitioners of electronic systems, semiconductor industries, and even SNI conceptors.

Keywords: spin coater, semiconductor industry, profilometer, performance characterization.

Abstrak

Saat ini, perkembangan industri semikonduktor sangat cepat dikarenakan tingginya permintaan pada sistem elektronik modern. Selain itu, nilai investasi di bidang elektronika juga meningkat lebih dari dua kali lipat selama tahun 2015-2017. Peningkatan investasi ini tentu berimbas pada peningkatan kebutuhan mesin pemroses bahan komponen elektronika/ semikonduktor. Untuk mendukung hal itu, telah didesain suatu spin coater yang berkinerja handal. Karakterisasi proses spin coating dilakukan di Badan Standardisasi Nasional (sebelumnya dikenal dengan Pusat Penelitian Metrologi LIPI) dengan menggunakan mesin ukur kekasaran permukaan/ profilometer yang tertelusur ke PTB (Jerman) untuk menjamin kebenaran hasil pengukuran. Eksperimen karakterisasi menggunakan fotoresis positif SPR3018 untuk melihat kinerja sistem yang didesain. Tiga eksperimen berbeda dijalankan untuk menentukan pengaruh kecepatan putaran dan waktu putaran pada ketebalan dan keberagaman fotoresis. Karakterisasi menunjukkan peningkatan kecepatan putaran, fotoresis lebih menyebar sehingga lebih tipis. Ketebalan fotoresis ditentukan berbanding terbalik dengan akar kuadrat dari kecepatan putar. Selain itu, semakin lama proses pelapisan, akan meningkatkan kecenderungan membentuk permukaan cekung. Artikel ini diharapkan memberi manfaat para praktisi sistem elektronik, industri semikonduktor, dan bahkan pembuat SNI.

Kata kunci: *spin coater, semiconductor industry, profilometer, karakterisasi kinerja.*

1. INTRODUCTION

The electronics industry is one of the contributors to Indonesian revenue. According to Indonesia industrial reports, the growth of the national GDP of the metal goods industry such as computers, electronics, optics and electrical equipment has decreased from 7.83% in 2015 to 2.79% in 2017 (Pusdatin Kemenperin, 2019).

On the other hand, the electronics industry in Indonesia, is prioritized to develop so that it can become part of the supply chain in the global market. The Indonesian Ministry of Industry noted, investment in the electronics industry reached IDR8.34 trillion in 2017. It reported increased more than twice compare to 2015 at IDR3.51 trillion (Kemenperin, 2019). This increase in investment is certainly intended to boost national GDP growth. Moreover, it also

will escalate the needs of raw materials and the number of machines to process raw materials into finished materials.

Furthermore, the energy availability is also one of the crucial problems now. Population growth and depletion of world oil reserves are the cause of the increasing demand for energy. Based on Presidential Regulation No. 5/2006 concerning the National Energy Policy, energy is power that can be used to carry out various process activities including electricity, mechanical energy and heat. In various energy utilization equipment, such as air conditioners, heaters, water pumps, and other electronic devices, there are always use components of semiconductor materials (Kristiningrum & Widyatmoko, 2012).

Semiconductors can be used to make various electronic components, both digital and analogue, and discrete or integrated. In modern era, semiconductor fabrication technology is growing rapidly following Moore's law. In order to improve product competitiveness in the global market, semiconductor products must be manufactured ideally. The way to improve the product can be achieved by increasing the characteristic of the products such as specification conformances, long term reliability and ability to meet industrial requirement (Larasati Kartika, Rahman & Ridwan Nugraha, 2017; Roblek, Meško & Krapež, 2016). In term of semiconductor standardization, National Standardization Agency of Indonesia (BSN) published two Indonesian national standard (SNI) , i.e.SNI IEC 60747-2:2009 and SNI ISO/TR 11811:2015 . This article provides some parameters on semiconductor making that may useful on semiconductor SNI formularization.

There are several processes needed to transform a silicon wafer to an integrated circuit. One of them is called photolithography. Photolithography is a process of transferring pattern from a mask to a substrate (Mack, 2007). The pattern is used to selectively cover an area for other process such as ion implantation or deposition. The impurity or thin film can be applied only to the target area. Photolithography played an important role in integrated circuit fabrication process line. Photolithography will create the components and interconnection between them.

A photoresist then required in order to transfer the pattern. It defined as a semiconductor material that sensitive to high energy light (ultraviolet) (Franssila, 2004). The exposure of ultraviolet light to photoresist will trigger the chemical reaction that alter its chemical structure. The photoresist can either be soluble or insoluble to a certain solution

depend on the type of the photoresist. One of the types of photoresist for microelectronics purpose is in liquid phase. A method called spin coating is needed to apply the photoresist on the substrate (Widodo & Nanang Sudrajad, 2014). Thickness and uniformity of photoresist on the substrate is important to make a perfect pattern.

Increased investment in the electronics sector in Indonesia, as stated earlier, will increase the need for electronic component processing equipment such as spin coater. most of the spin coater available on the market is very expensive. Several researches were done in designing of spin coater (Ferdaus, Rashid & Rahman, 2014; Hossain, Paul, Raihan & Khan, 2014; Patiño-Herrera, Catarino-Centeno, González- Alatorre, Gama Goicochea & Pérez, 2017), but none of it, characterized the designed spin coater using traceable to international system of unit (SI) apparatus.

This research focussed on the design of spin coater that has well performed angular speed sensor, good control accuracy, simple user interface, liberation on setting the angular velocity profile, and made with materials that are easily obtained in the market and relatively cheap. Characterization of spin coating process was done by traceable to SI-apparatus. It analysed the relationship between photoresist thickness and angle velocity of motor as well as factor analysis affecting homogeneity of photoresist. This article provides an overview of reliable prototype spin coater machine, so it is expected to benefit the practitioners of electronic systems, the semiconductor industry, and even the SNI conceptors.

2. BASIC THEORY

There are many parameters that have significant impact on photoresist thickness and uniformity such as wafer cleanliness, spin speed, spin time, and acceleration to each of the spin speed. However, temperature, humidity, spin chamber geometry, and spinner cleanliness often have significant effect on the resist film (Du et al., 2016; Hess & Reinhardt, 2018).
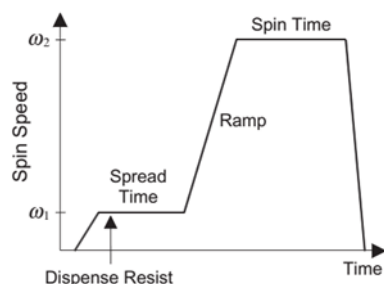
Figure 1 General spin coating cycle (Mack, 2007)

Figure 1 shows photoresist spin coating cycle. In general, there are two stages of spin coating i.e., spread stage and spin stage. Spinning makes the liquid photoresist rushes to the edge of the wafer due to the centrifugal forces. The internal friction forces of the photoresist blocked the centrifugal forces as shown in Figure 2. Evaporation makes the viscosity of the photoresist or the friction forces increase. Once after spinning began, the friction force negates the centrifugal forces and the resist stops flowing. Evaporation process takes over from this moment making the resist thinner (Mahmoodi, Guoqing & Khajavi, 2016; Weidner, Schwartz & Eley, 2019).
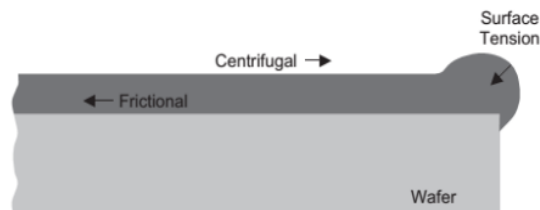

Figure 2 Forces work on resist during spin coating process (Mack, 2007).

The block diagram of spin coater system design is shown in Figure 3. The system consists of STM32F4 arm-based microcontroller, 4x4 keypad, LCD, seven segment display, as well as motor and sensor. Keypad and LCD is used a user interface to set the spin coating parameters while seven segment display is used to display the spin speed.
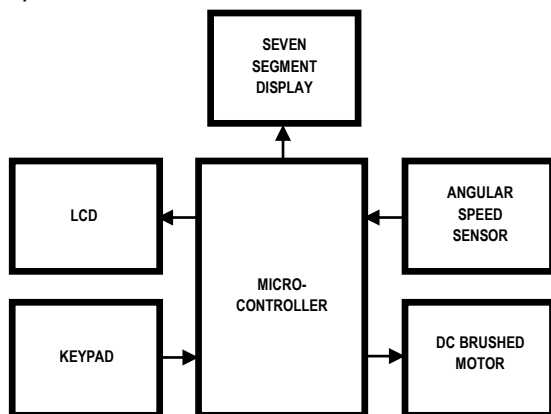

Figure 3 Block diagram of the spin coater system.

Inside the motor compartment, there are motor, driver, and angular speed sensor. The motor used is a brushed DC motor. It has spinning rate up to 10000 rpm. High current needs to drive the motor. Transistor that can be used to fulfill that is IRF3205. It is a kind of MOSFET that can supply up to 55 A continuous

current (Rectifier, 2019). The major setback of using MOSFET is the existence of gate to source capacitance. The capacitor need time to charge make the rising time on the gate of the capacitor longer. This problem can be overcome with high current supply on the gate. There are many IC manufactured to fulfill this purpose. TLP250 is an IC to drive a MOSFET that can supply current up to 1 A on the gate (Toshiba Corp., 2019). The complete circuit of the motor driver is shown in Figure 4. Protective diode is added parallel to the motor to protect the transistor from high feedback voltage.
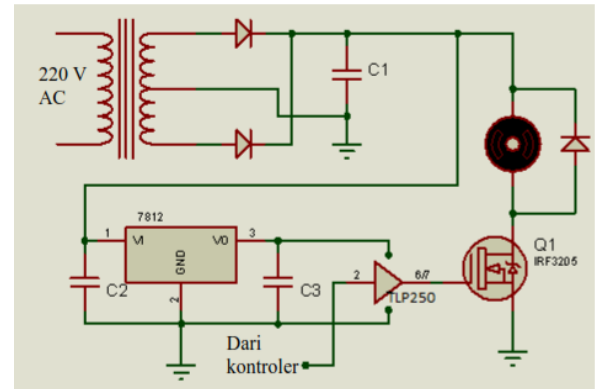

Figure 4 Motor driver circuit.

To measure the angular speed of the motor, Hall effects sensor a3144 and a few of neodymium magnet are used. It works by Hall effect principle (Honeywell, 2016; Song, Fang & Han, 2015; Yu, Zhang & Huang, 2017). The Hall effects sensors are attached to the body of the motor while the magnets are attached to circular object which attached to the shaft of rotating rotor (Figure 5).
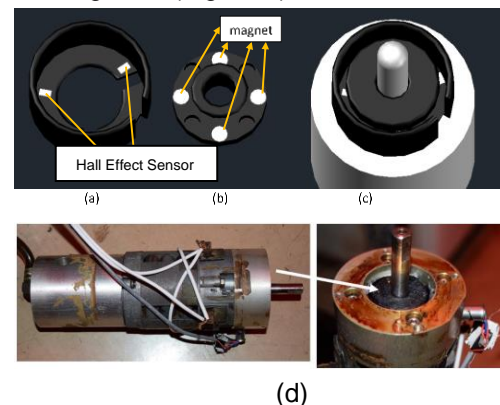

(d)

Figure 5 Motor system; (a) Hall effects sensors; (b) Neodymium magnets; (c) Insertion on the motor body and rotor; (d) Motor embedded with the sensors.

The configurations will enable the measurement time between two events, later the angular speed of the rotor can be determined. Two sensors and four magnets are used as angular speed sensor. The sensor is placed at 135° so they yield signals that is out

of phase. With this configuration, one full rotation is marked by 8 (eight) signals. One signal is equal to one-eighth rotation. The angular speed (ω) of the motor as a function of signal period (τ) is calculated by equation (1).

$$\omega = \frac{1/8}{\tau} rps = \frac{60}{8\tau} rpm \tag{1}$$

STM32F4 microcontroller is the heart of the system. The microcontroller run freeRTOS kernel to deal with multi-tasking. There are four tasks and two interrupt service routine (ISR) on the system as shown in Figure 6. Display LCD task is the task that responsible for displaying the LCD, seven segment task is the task that in control of the spin speed displaying the seven segment, keypad task is the task that in charge of scanning the input and take appropriate action, while control and sampling task is liable for sampling the speed and control the speed of the motor. Two ISRs are called when the magnet passes the sensor. It responsibles on measuring the time between those events.
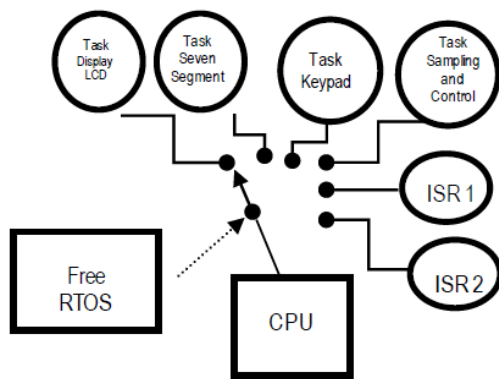

Figure 6 Software design.

Furthermore, the proportional, integrative and derivative (PID) control system is used to control the speed of the motor. Ziegler-Nichols method is used to tune the PID control parameter (Díaz-Rodríguez, Han, Keel & Bhattacharyya, 2017; Hassan, Zolotas & Smith, 2017; Kamarudin et al., 2018). The proportional gain is increased without integration and derivative of the gain until continuous oscillation occurs at gain Ku. The period of the oscillation at this gain is called Tu. The control parameter is then determined using the value of Ku and Tu. The proportional gain is 0.6 Ku, the integration time is 0.5 Tu, and the derivative time is 0.125 Tu. After several trial and error, the optimum control parameter for the system developed for proportional gain, integration time and derivative time are 0.06, 0.48 and 0.12 respectively.

3. METHODS

Spin coater that already designed (see Figure 7) has angular velocity up to 10000 rpm with resolution less than 50 rpm, motor speed control accuracy within 50 rpm. The spin coating time also can be adjusted up to 999 second with 1 second resolution. LCD and the keypad for the user interface are placed on the top of the cup along with the seven segments display. The switch to turn on the spin coater is on the right of the cup.

The wafer that used for spin coating process should be cleaned before being used. The wafer that is used must be very pure from organic contaminants and micro dust. All the wafer cleaning processes were done in a clean room. The room is conditioned so that contaminants are very minimal in the room. The instrument used for soaking and washing is a beaker 250 ml so that the volume can be controlled. It was cleaned by using hydrogen peroxide 50%, 5 M sulfuric acid, acetone 97%, Nitrogen gas 99% and distilled water. Firstly, the wafer is soaked in a solution consist of 30 ml of H_2O_2 and 60 ml of H_2SO_4 for 15 minutes. It rinsed with distilled water on ultrasonic cleaner for 5 minutes as many as 3 times, while next process was by soaked it into acetone 95% for 15 minutes and rinsed again with distilled water. Nitrogen gas with 99% purity is used to remove water remnant on the wafer. Finally, it then baked for 15 minutes at 115 °C.

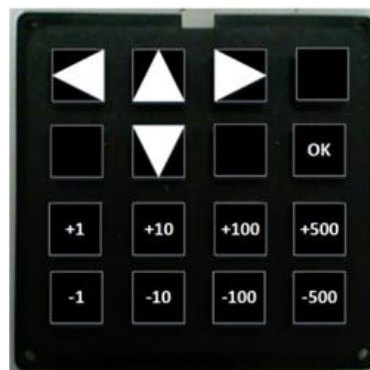

Figure 7 Spin coater and the keypad view.

Table 1 Fixed parameters for first experiment.

Parameter	Value
Spread speed	1000 rpm
Spread time	5 s
Ramp up	10000 rpm/s
Spinning time	30 s
Ramp-down	3000 rpm/s

There are three different experiments to determine the impact of spin speed, ramp-up acceleration, and spin time on the thickness and uniformity of photoresist. The fixed parameters of first experiment are shown on Table 1. The spin speed is changed from 2000 to 6000 rpm with 1000 rpm interval. The sample with photoresist on it is scratched to know the depth (see Figure 8).

Table 2 Fixed parameters for second experiment.

Parameter	Value
Spread speed	1000 rpm
Spread time	5 s
Ramp up	3000 rpm
Spinning time	30 s
Ramp-down	3000 rpm/s

The second experiment uses parameters as shown in Table 2 as fixed parameters while the ramp-up acceleration is changed from 2500 to 7500 rpm/s with interval of 2500 rpm/s. The third experiment uses parameters as shown in Table 3 as fixed parameters while the spin time is changed to 35 s and 60 s.

Table 3 Fixed parameters for third experiment.

Parameter	Value
Spread speed	1000 rpm
Spread time	5 s
Ramp up	10000 rpm/s
Spin speed	3000 rpm
Ramp-down	3000 rpm/s

The characterization of wafers that produced by spin coater were done by using Talysurf i120 roughness measuring machine/ profilometer at BSN (formerly was known as RCM-LIPI). The traceability of measurement to international system of unit is through PTB, Germany by type A1 depth measurement standard artifact (International Organization for Standardization, 2000). Traceability chain intended to guarantee the measurement results validity. Before characterization process, type A1 artifact should be measured by roughness measuring machine to get the correction factor. It will be used as a multiplication factor to waviness parameter as the measured result to prevent the biased of the measurement (Halle GMBH, 2019; Koenders, Andreasen, De Chiffre, Jung & Krüger-Sehm, 2004; Vorburger et al., 2008). Furthermore, waviness parameter (International Organization for Standardization, 1997) is used for uniformity analysis.

4. RESULTS AND DISCUSSIONS

Figure 8 shows typical wafer that processed by our designed spin coater. Scratches on the surface intended for photoresist thickness analysis and labelling purposes. Analysis of characterization results separates into two photoresist features which are thickness and uniformity.
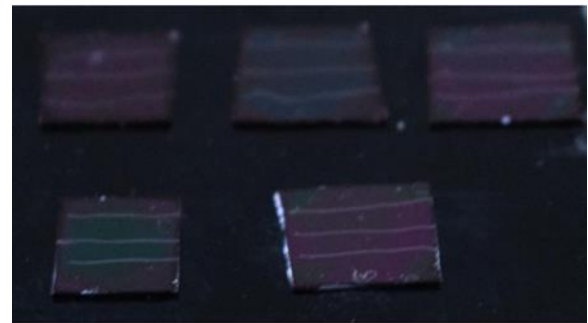

Figure 8 Wafer produced by our spin coater.

The variation of photoresist thicknesses (d) related to spin speeds from the experiments are shown in Table 4. Best fit for the experimental data is $d = \dfrac{54.8}{\omega^{0.45}}$ with r-squared of 0.99; where d is the thickness of the wafer in mm, and ω is the motor speed in rpm. As a note, r-squared, in this case, is commonly used in describing the quality of data fitting (Adinugroho, Susanto, Isharyadi, Kristianingrum & Mustar, 2015; Little & B. Rubin, 2019). According to theory, the thickness of the photoresist is inversely proportional to the square root of spin speed.

For this criterion, the fit for the data is $d = \dfrac{83.4}{\sqrt{\omega}}$ with r-squared of 0.92.

Table 4 Photoresist thickness (d) from experiment.

Spin speed (rpm)	Thickness (mm)
2000	1.8
3000	1.5
4000	1.3
5000	1.2
6000	1.1

The comparison between fitting, experimental data and theory are shown in Figure 9. In general, both experiment and theory have values that are not much different as shown in Table 5. At a rotation below 3000 rpm the graphs coincide. In the other hand, at high rotation the difference is greater value although not significant. It can be seen, the

difference between theoretical fit and best data fit are not exceeding 4% so that insignificant. This shows very good performance of spin coater designed.
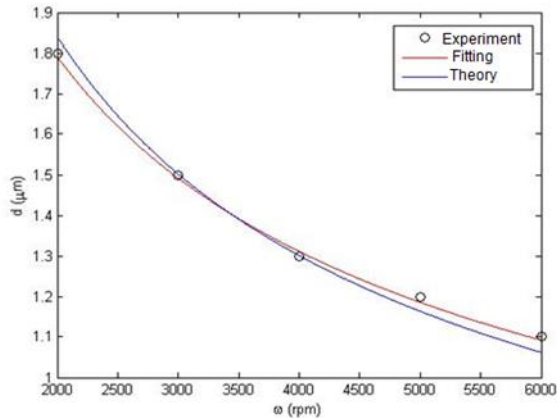

Figure 9 Relation of photoresist thicknesses and spin speeds.

Table 5 Experimental and theoretical data fitting comparison.

Spin speed (rpm)	Thickness (experimental data fitting) (mm)	Thickness (theoretical data fitting) (mm)	Differences (%)
2000	1.79	1.86	4.07
3000	1.49	1.52	1.98
4000	1.31	1.32	0.53
5000	1.19	1.18	0.59
6000	1.09	1.08	1.49

Figure 10 shows the images of photoresist uniformity from the first experiment. It is done to see the effect of the speed rotation (rpm) to the photoresist surface profile. Note that three flaws which are shown on Figure 10 are scratches for labelling and depth analysis purposes (see also Figure 8 for view comparation). Z-axis on Figure 10, Figure 11 and Figure 12 are the contour heights are sensed by roughness measuring machine. On first experiment, the surface of the wafer tends to become concave as the speed increase. The most uniform surface achieved for spin speed of 4000 rpm with waviness of 0.07 mm. We repeat the procedure several time. We found that the designed spin coater has good performance in resulting very good waviness of wafer. The waviness of surface of the wafer is not varied more than 10%.
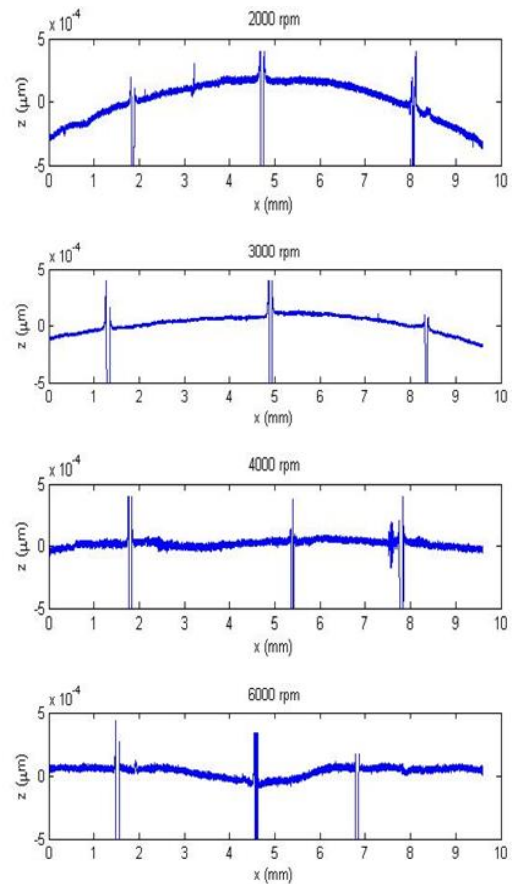

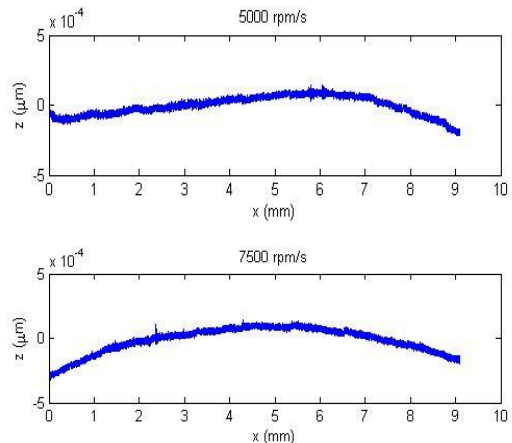Figure 10 Photoresist profile from the first experiment.

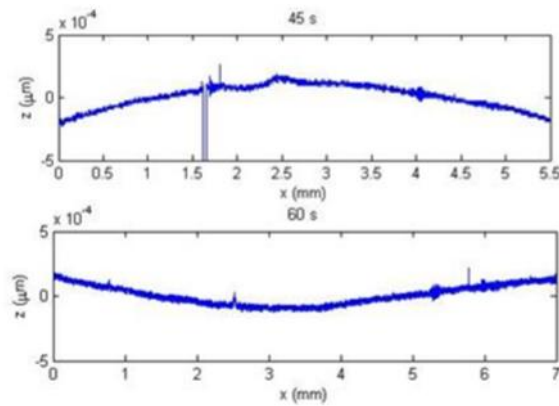Figure 11 Photoresist profile from the second experiment.

Figure 12 Photoresist profile from the third experiment.

Photoresist uniformity from the second experiment is shown in Figure 11. The second experiment aims to see the effects of ramp-up acceleration (in rpm/s) to the photoresist profile uniformity. Ramp-up acceleration increased from 5000 rpm/s to 7500 rpm/s. It is found that, the surface intended to stay convex regardless of the increasing of ramp-up acceleration. As a result, it can be concluded, the ramp-up acceleration does not have significant impact on photoresist uniformity.

Figure 12 shows the results of third experiment that is intended to see the effects of the spinning time (in second) to the waviness of the surface. Spinning time of 45 second and 60 second were shown sequentially. Spinning time of 45 second photoresist surface was in concave form, while spinning time of 60 second the surface was concave. It can be said that the surface of the photoresist changed from convex to concave as the spin time longer. From this phenomenon, it can be concluded that the surface of the photoresist tends to become concave as the spin time longer.

Several researches were done in designing of spin coater (Ferdaus et al., 2014; Hossain et al., 2014; Patiño-Herrera et al., 2017), but none of it, characterized the designed spin coater using traceable to international system of unit (SI) apparatus as this research did. The validity of the characterization results is more trustable if the characterization processes done by traceable apparatus. Furthermore, compared to the previous experiment about fabrication and characterization of spin coater, it was conformed by Ferdaus (Ferdaus et al., 2014), it had simmilar phenomenon as what this research described.

Ferdaus had reported that the result of performance test was done by making a ZnO thin film. These films were prepared by sol-gel process and deposited on the glass substrate of the spin coater. During the spinning of the substrate the fluids flows up to the edges of the substrate. It was also observed in our experiment as shown in Figure 12. Differed from Ferdaus experiment which used 3000 rpm motor to control the spinning speed by changing the voltage supply, this research used Hall effect sensor to control the spinning speed. The most uniform surface reached at the spinning speed of 4000 rpm and spin time of 30 s. The difference might be caused by the type of sample used.

In general, the result showed that the thickness of the photoresist is inversely proportional to the square root of spin speed. Otherwise, to get homogeneous films, several issues are significant and must be considered in the future research, such as solution viscosity and concentration, the evaporation rate of the solvent, and lightning time.

5. CONCLUSION

It has been designed well performed spin coater that embedded with LCD, keypad and seven segments for controlling and adjusting the spin coating time, motor speed and angular velocity of the motor. The characterization of spin coater was used traceable to SI apparatus so that the characterization result can be trusted and valid. The result shows the thickness of the photoresist is inversely proportional to the square root of the spin speed. Ramp-up acceleration has insignificant impact on photoresist uniformity, because the uniformity of photoresist not only affected by the acceleration of centrifugal force but also affected by the velocity and characteristic turbulence of the air due to concentration. In contrary, spin time has significant impact. Moreover, the longer spin time, the surface of the photoresist tends to become concave, because the fluid flows up to the edges of the substrate. The most uniform surface was achieved at spin speed of 4000 rpm and spin time of 30 s. Further studies of other parameters such as, the impact of wafer geometric and lighting time on thickness and uniformity of photoresist need to be done in the future.

national measurement standards for length of Pusrisbang – BSN for their constant encouragement, support, and useful discussions.

DAFTAR PUSTAKA

Díaz-Rodríguez, I. D., Han, S., Keel, L. H., & Bhattacharyya, S. P. (2017). Advanced tuning for Ziegler-Nichols plants. *IFAC-PapersOnLine*, *50*(1), 1805–1810.

Du, L., Yang, T., Zhao, M., Tao, Y., Luo, L., Wang, L., & Liu, C. (2016). Study on improving thickness uniformity of microfluidic chip mold in the electroforming process. *Micromachines*, *7*(1), 7.

Ferdaus, M. M., Rashid, M. M., & Rahman, M. A. (2014). Design and fabrication of a simple cost effective spin coater for deposition of thin film. *Advances in Environmental Biology*, *8*, 729-733.

Franssila, S. (2004). *Introduction to micro fabrication*. Helsinki: Wiley.

Halle GMBH. (2019). *Depth setting standard technical A1 data*. Retrieved February 4, 2019, from http://www.halle-normale.de/pdf/Prospektseiten/englisch/05 Ps-KNT-4080_03-Bl_1-5_GB.pdf

Hassan, F., Zolotas, A. C., & Smith, T. (2017). Optimized Ziegler-Nichols based PID control design for tilt suspensions. *Journal of Engineering Science and Technology Review*, *10*(5), 17–24.

Hess, D. W., & Reinhardt, K. A. (2018). *Plasma stripping, cleaning, and surface conditioning.* In Handbook of Silicon Wafer Cleaning Technology. William Andrew Publishing.

Honeywell. (2016). *Hall effect sensing and application*. Retrieved from https://sensing.honeywell.com/honeywell-sensing-sensors-magnetoresistive-hall-effect-applications-005715-2-en2.pdf

Hossain, M. F., Paul, S., Raihan, M. A., & Khan, M. G. (2014). Fabrication of digitalized spin coater for deposition of thin films. *IEEE - International Conference on Electrical Engineering and Information & Communication Technology*, 1–5.

International Organization for Standardization. (1997). *ISO 4287:1997(en), Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Terms, definitions and surface texture parameters.*

International Organization for Standardization. (2000). *ISO 5436-1:2000(en), Geometrical Product Specifications (GPS) — Surface texture: Profile method; Measurement standards — Part 1: Material measures.*

Kamarudin, M. N., Rozali, S. M., Hairi, M. H., Hanaffi, F., Aras, M. S. M., & Zambri, M. K. M. (2018). Realization of Real-Time Hardware-in-the-Loop for a Liquid Level with Open-loop Ziegler Nichols Technique. *International Journal of Electrical Engineering and Applied Sciences (IJEEAS)*, *1*(2), 47–52.

Kemenperin. (2019). *Peningkatan investasi industri elektronika perkuat struktur manufaktur*. Retrieved September 11, 2019, from https://kemenperin.go.id/artikel/19352/Peningkatan-Investasi-Industri-Elektronika-Perkuat-Struktur-Manufaktur

Koenders, L., Andreasen, J. L., De Chiffre, L., Jung, L., & Krüger-Sehm, R. (2004). EUROMET Project 600 - comparison on surface roughness standards. *Metrologia*, *41*(1A), 4001.

Kristiningrum, E., & Widyatmoko, W. (2012). The Study of Electronic Equipment Household Products Standard in Supporting Energy Efficiency. *Standardisasi*, *14*(3), 182–197.

Larasati Kartika, N., Rahman, A., & Ridwan Nugraha, A. (2017). Effect of stylus position shiftings to eccentricity and roundness value in glass hemisphere measurements. *Instrumentasi*, *41*(2), 57–63.

Mack, C. (2007). *Funcamental principles of optical litography*. Texas: Wiley.

Mahmoodi, S., Guoqing, H., & Khajavi, M. N. (2016). Two-dimensional spin coating with a vertical centrifugal force and the effect of artificial gravity on surface leveling. *Journal of Coatings Technology and Research*, *13*(6), 1123–1137.

Osaka, T., & Hattori, T. (1998). Influence of initial wafer cleanliness on metal removal efficiency in immersion SC-1 cleaning: Limitation of immersion-type wet cleaning. *IEEE*, *11*(1), 20–24.

Patiño-Herrera, R., Catarino-Centeno, R., González-Alatorre, G., Gama Goicochea, A., & Pérez, E. (2017). Enhancement of

the hydrophobicity of recycled polystyrene films using a spin coating unit. *Journal of Applied Polymer Science, 134*(40), 45365.

Pusdatin Kemenperin. (2019). *Analisis perkembangan industri* (1st ed.). Retrieved from https://kemenperin.go.id/download/21653/Laporan-Analisis-Perkembangan-Industri-Edisi-I-2019

Rectifier, I. (2019). *IEF3205 datasheet.* Retrieved February 1, 2019, from www.irf.com/product-info/datasheets/data/irf3205.pdf

Roblek, V., Meško, M., & Krapež, A. (2016). A complex view of industry 4.0. *Sage Open, 6*(2), 2158244016653987.

Song, X., Fang, J., & Han, B. (2015). High-precision rotor position detection for high-speed surface PMSM drive based on linear Hall-effect sensors. *IEEE Transactions on Power Electronics, 31*(7), 4720–4731.

Toshiba Corp. (2019). *TLP250 datasheet.* Retrieved February 2, 2019, from https://toshiba.semicon-storage.com/info/docget.jsp?did=16821&prodName=TLP250

Vorburger, T. V., Renegar, T. B., Zheng, A. X., Song, J. F., Soons, J. A., & Silver, R. M. (2008). *Nist surface roughness and step height calibrations : Measurement conditions and sources of uncertainty.* 1–7. Retrieved from https://www.nist.gov/sites/default/files/documents/pml/div683/grp02/nistsurfcalib.pdf

Weidner, D. E., Schwartz, L. W., & Eley, R. R. (2019). Numerical modeling of the spray coating of spinning bodies. *Journal of Coatings Technology and Research, 16*(2), 363–376.

Widodo, S., & Nanang Sudrajad. (2014). The process of photolithography in semiconductor device manufacturing. *Prosiding Seminar Nasional Fisika*, 306–316.

Yu, L., Zhang, Y., & Huang, W. (2017). Accurate and efficient torque control of an interior permanent magnet synchronous motor in electric vehicles based on hall-effect sensors. *Energies, 10*(3), 410.