

Design and implementation of a feedback programmable spin coating system

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ABSTRACT

In this work, a speed controlled, the programmable, low-cost, high-efficiency spin coating system is designed and implemented. The system is built from commercially available hard disk drivers DC motor, vacuum pump, speed sensor, brushless driver circuit carries Toshiba's TB6575FNG IC, PIC18F47J53 Microcontroller and using the interactive user interface to communicate with a user. Three different voltage stages and pulse width modulation techniques were used to guarantee accurate spinning speed and time. This system provides a wide range of precise and stable multi-step speeds rang of 1500 to 8,000 rpm. To evaluate the implemented system, ZnO thin films have been deposited by the sol-gel method on a glass substrate. Homogenous and uniform thickness films were obtained. The outstanding features of this system are the stability, accuracy, low energy consumption and durability, and the simplicity of adjusting multi-step spinning speed and time by using the interactive user interface.

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1. INTRODUCTION

Thin film deposition technique plays a key role in the electronic and optical applications manufacturing. Various techniques have been used to deposit thin films, including sputtering [1], chemical vapor deposition [2], thermal evaporation [3], spray pyrolysis [4], dip-coating [5, 6], electro-deposition [7] and spin coating [8]. As compared to other deposition techniques, spin coating is faster, *easier*, cheaper and need a small amount of depositing material [9]. In this technique, the thin films are deposited by employing centrifugal force concept, by adopting on speed-time changes [10, 11]. The thickness of a film is a result of a balancing of two main opposing forces namely: centrifugal force and viscosity force. The thin film thickness is significantly depending on spinning speed, solution viscosity and substrate type. During the rotation process, the centrifugal force overcomes gravity and produces rapid thinning of the film [10, 11].

There are many commercial spin coating systems available, however, many researchers have been and still proposed to build spin coater for research purposes [10, 12-14]. Most of the spin coater based research purposes work utilized brushless DC motor (BLDC motor), that usually employed as a computer hard drive using pulse width modulation (PWM) to control DC motor speed. PWM is a recognizable technique used to precise control DC motor speed by a controller circuit [15]. The speed is controlled by the average amount of power fed to the motor. By controlling the ON conduction time duration per cycle, the amount of voltage applied to the motor can be controlled. Changing the working cycle is employed through the built-in Module in the controller circuit [16]. In addition, the feedback control system is essential to be deployed to get accurate spinning speed [14]. To solve the *degradation* of spinning speed over long-term utilization. Also, to confirm the accurate spinning speed, regardless of the shape, size and mass

substrates, within the limit of the system capabilities. However, most of the previously reported works are quite simple without the feedback circuit and using a single stage voltage [10, 12-14].

In this work, a developed programmable feedback spin coating system has been designed and implemented for an actual need of our research laboratory. The system is low cost, efficient and durable, low energy consumption and easy to operate. The system is built from a commercially available DC motor in HDD, vacuum pump, 12 V power supply, IR sensor, brushless click carries Toshiba's TB6575FNG IC and PIC18F47J53 Microcontroller, as well as to the external system body. The system is connected to the computer by Human interface device (HID) protocol for bi-directional communication, a serial transfer technology was used via the USB port. Three different voltage stages have been applied to obtain a smooth and wide variable range of spinning speed. An Infrared (IR) circuit was employed to sense the real-time precise spin speed. PIC18F47J53 microcontroller program was written using MikroC language which includes a variety of libraries to support the chip modules. The performance of the system was evaluated by coating ZnO sol-gel on glass substrates. The relation of the thickness of the films with the spinning speed and spinning time were investigated. Thin, consistent, controlled films was obtained.

2. RESEARCH METHOD

We utilized a commercially Brushless DC Motor (BLDC motor), as shown in Figure 1(a), that usually employed as a computer hard drive. This motor is proposed because it can be precisely controlled with a very long operating life, small dimensions, and high acceleration [10]. To hold the substrate, the suckering process is implemented. Thus, the BLDC rotor axis was hollowed out with a high-speed steel drill with a diameter of 5mm. A special nozzle is attached to the lower side of the hollow rotor axis through a hose and connects to the outlet of the vacuum pump. To ensure there is no leakage could be exists at the contact area between the nozzle and lower face of the dc motor, a special arrangement (consist of O-ring and spring thrust on the nozzle) is used. This arrangement allows the motor rotor to rotate freely and at the same time it's providing enough value of vacuum pressure to hold specimen on the DC motor dram. The vacuum pump model 1.5 CFM VH115N is chosen based on the friction force calculations. The motor torque is sufficient to fix the lightweight substrates (Si, glass, sapphire) for the required spinning speed range (1500 to 8000 rpm). The substrate holds on the top of the BLDC rotor drum during the coating process. This fixing method is preferably more than the adhesive material method, to avoid any damage could happen to the specimen after complete coating.

The PWM control technique is used to accurately control the spinning speed of the motor. PWM is done by sending different duty cycle (the variation in the ON state to OFF) with a fixed voltage. The device spinning speed relies on the supplied average power which has been formed as a wave of pulses (PWM) duty cycle. The supplied average power enforce the motor coils to produce a different torque and then different speed. Hence, the driver controls the rotation speed by changing the PWM duty cycle (D). For example, if the voltage reference of the driver is 10 V then the supplied voltage ($V=(10/100) \times D$) [14]. For the maximum value of designed spinning speed (8000 rpm), the obtained spinning speed ($\omega=(8000/10) \times V$). Hence, the relation of speed as a function of the duty cycle can describe, $\omega=(8000/100) \times D$. If the duty cycle 100% gives the maximum speed.

2.1. Control Circuit

The controller circuit is built with a Microchip PIC18F47J53 microcontroller. The PIC18F47J53 microcontroller chip is one of the 18F family 8-bit architecture. This chip has different built-in modules. Table 1 listed the different modules used in this work to achieve the system implementation requirement. Figure 1(b) shows an image of the PIC18F47J53 microcontroller chip. Since the microcontroller output power is very small, a brushless motor driver called Brushless Click is utilized to enable the microcontroller to drive the 3-phase full-wave BLDC motor. The Click board manufactured by Mikroelektronika Company contains a TB6575FNG chip. The TB6575FNG chip is a three-phase PWM controller for sensorless BLDC motors. Figure 1(c) shows an image of the utilized Brushless Click.

Table 1. Modules used in the Project

Module Name	Function in the project
PWM	Controlling the BLDC
GPIO	Emergency switch, Indication LEDs
Timers	Calculating time and counting some external signal to extract motor speed
USB	To establish a connection between the microcontroller and the PC

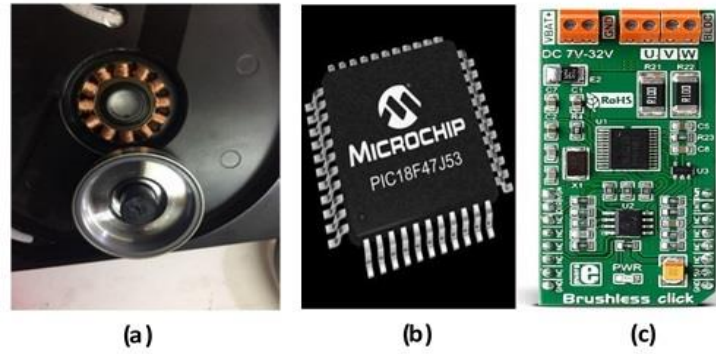


Figure 1. A photo-image of the (a) Brushless motor shows rotor, shaft, and coils, (b) Microchip PIC18F47J53 microcontroller, (c) Brushless click

To ensure the stability of spin speed, a feedback control technique was designed, simulated and employed. The purpose of the feedback control circuit is to compare the desired speed with the measured speed. An error is recognized when there is a difference between these two values. The error translated through a proportional-integral-derivative (PID) controlling algorithm to decide the required acceleration or damping that important for spinning speed integrity [17-19]. The feedback control circuit alongside the USB communication is designed and simulated using the Proteus simulation system (Design Suite by Labcenter Electronic “version 8.5”). The Proteus simulation is used to operate and test the electronic circuitry before it is actually implemented. The speed sensor was replaced with a pulse generator and the motor control circuit replaced by an oscilloscope. Figure 2 illustrates the simulation of the feedback control circuit design by Proteus system.

To operate the system, the user has to enter particular parameters (Speed and Interval) and to translate that in the MCU, a combination of timer-counter scheduling value has been used. In the microcontroller two timer modules used to synchronize system timing and accomplish user setup. Timer 0 and timer 3 have been carefully chosen to operate the system tasks that related to any time scheduling tasks required. Figure 3 shows the flowchart of the timers running sequence to calculate the spinning speed and intervals. As shown in the chart, timer 0 uses to count the user interval by creating the timer interrupt each 1 second and count these seconds until approach the destination value of user interval in seconds. During this 1 second calculation, timer 3 uses to count the number of pulses each 1 second. These pulses represent the number of cycles that come from the IR module (rpm).

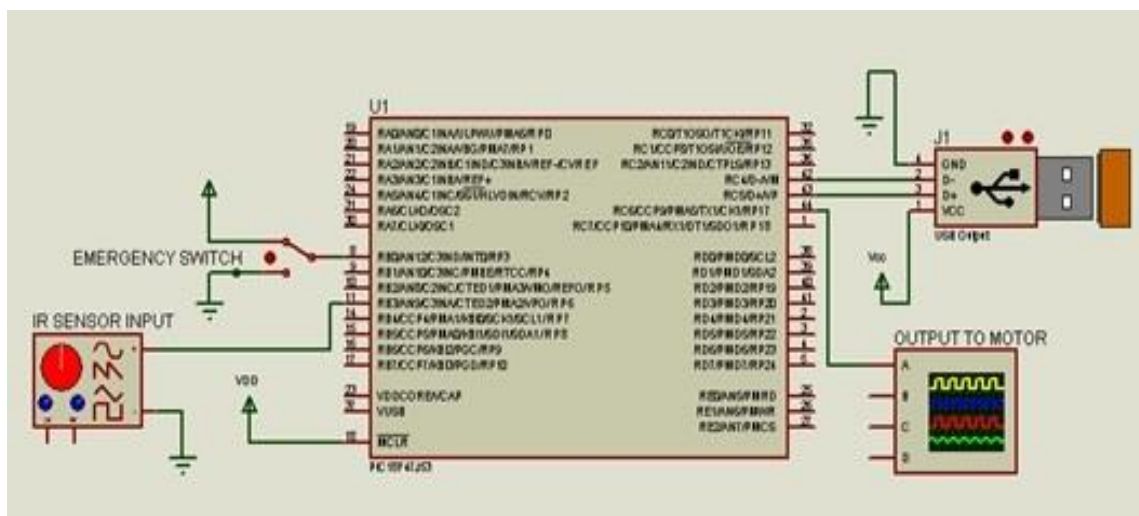


Figure 2. Simulation of the feedback control circuit design by proteus system

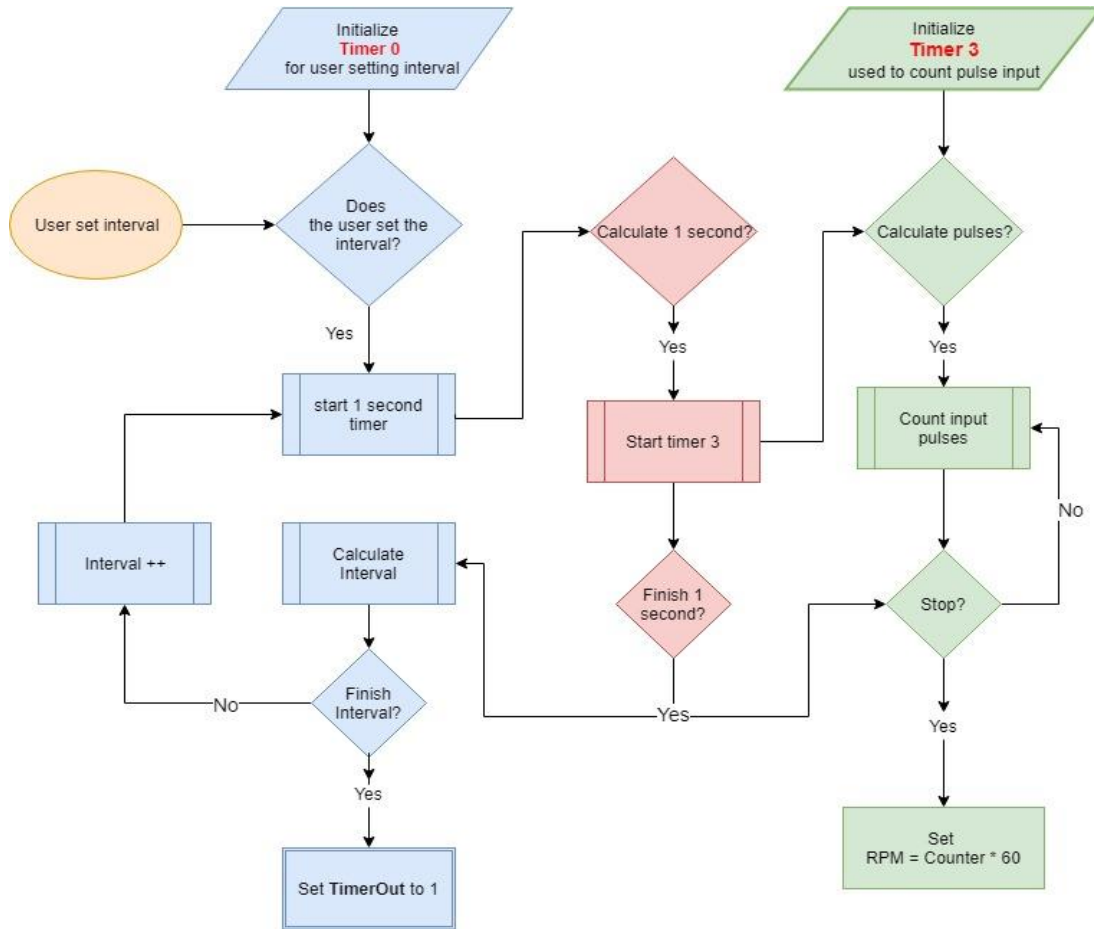


Figure 3. Timers running sequence flowchart

Users use a computer application user interface to enter test parameters. Tests can be done by two modes of operation: standard and manual mode. In the standard mode particular sets of the sequence have been stored and ready to use directly, while in manual mode the user free to select the task parameters whether it is a single-step or multi-step task, and what is the speed and interval for each step. By pressing the run button a connection between the computer and the device established, and user test parameter transferred to the device inside the MCU. The MCU creates combinations of timer-counter settings and lets the timer modules execute them. For example, to apply two multi-step spinning speed, the interaction box allows the user to enter two types of spinning tasks. The tasks will execute alternately, first speed and interval and then the second speed and interval. The feedback control mechanism utilized by the number of pulses generated from the Infrared (IR) sensors and faded back to the microcontroller through a calibration circuit [20]. IR speed sensor is used to measure the spinning speed without affecting the speed of the motor. The working principle of the sensor can be summarized by, the IR LED transmitter sending continuously the infrared waves to the moving part of the engine and receive the reflective signals via the IR photodiode receiver continuously. A selected portion of moving part of the motor dye with black color, because the black dye absorbs the largest amount of infrared radiation (low value of reflectance). As a result, the signal generated by the photodiode receiver is a pulse in the number of rotation cycles. Within the PIC18F47J53 microprocessor, a function is created to calculate the pulses generated by the signal received from an IR photodiode per second.

2.2. Spinning Speed Calculations

In order to achieve a wide range and a high resolution of the operation speed of spin coater apparatus, three different voltage stages have been implemented 5, 7 and 10 V. The three voltage stages implementation extracted based on experimental measurements. It is found to be the three stages technique gives a smoother and wider range of spinning speed than single voltage stage. According to the extracted data, a special driving circuit is developed to control the motor speed of the studied spin coater apparatus.

The spin coater apparatus can run at the desired rotational velocity by mean of maximum speed and control the PWM duty cycle. However, the experiment shows that the supply voltage level can shift the spinning rang. The spin coater system performance has examined experimentally before final setting to extract the expression to relate spinning speed, duty cycle and supplied voltage. It is found to be that, each supply voltage stage, gives a specific range of running speed of the spin coater during the variation of the duty cycle of PWM. Figure 4 illustrates the manner of actual spinning speed changing with supply voltage range from 5 to 10 V and the entire duty cycle of the PWM signal as the 3 dimensional surface. The fit tools with linear interpolation are used to plot a 3 dimensional surface in MATLAB package. It is clearly seen from Figure 4 that the BLCD motor behave differently with different supplied voltages. The duty cycle versus spinning speed plan shows that, for all studied voltages, the speed rises with increasing the duty cycle until reach a particular value of D, then after this particular value the velocity tends to saturate. For example, for 5 V input level, when the D equal to 35% the velocity is 1500 rpm, by increase the D the speed increases accordingly, however, the velocity statured at 3840 rpm when the duty cycle above 68% up to 100%. Hence, the spinning speed velocity range is 1500 to 3840 rpm for 5 V applied voltage level, which is much lesser than the speed range capability of BLCD. For 7 V applied voltage the speed is 2640 rpm for 35% D, the spinning increases with increases the duty cycle, the speed started to be saturated 5460 rpm at 64% up to 100% D. Similarly, for 10 V stage, the speed is 4380 rpm for 35% D, the speed started to be saturated 7920 rpm at 60% up to 100% D. Accordingly, three platforms technique deployed to the proposed system to get the full range 1500 to 7920 rpm. Table 2 summarizes the three stages of performance. Consistently, based on the extracted data, the PID controller was designed to control the duty of PWM signal of the dc motor to ensure that the error between desired and actual running velocity has the minimum value.

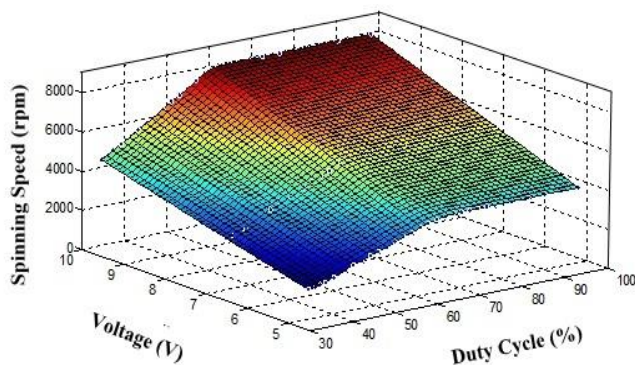


Table 2. The Three Stages of Performance

Input Voltage Stage (V)	Initial Velocity (rpm)@ 35% D	Saturated Velocity (rpm)	D (%) @ Saturated Velocity
5	1500	3840	68
7	2640	5460	64
10	4380	7920	60

Figure 4. The measured spinning speed changing with supply voltage and duty cycle of PWM signal as 3 dimensional surface

2.3. Connect the System to the Computer

In order to connect the system to the computer, a serial transfer technology was used via the USB port. Human interface device (HID) protocol is a technology allows the external devices to be connected to the computer by supported bi-directional communication. The PIC18F47J53 microprocessor has the ability to output data to the computer via USB HID protocol and vice versa. HID has an efficient working inbuilt library and does not require any additional library or devices. The system is developed and programmed by using MikroC compiler from Mikroelektronika using USB HID library and USB descriptor tool.

2.4. Spin Coating System Construction

The circuit and the motor were fixed in a wood box of 20x20x10 cm³ with the axis of the motor passing through the spill container. A Teflon (Multi-tetrafluoroethylene) spill container has been fabricated to get the desired spinning stage in order to reduce material splashing and wasting. The spill compartment Teflon cover with a heavy glass window slot to allow visibility and safety during the coating process. Teflon has been chosen because of its unique properties. It is a durable, available and chemically inert material that does not react with acids, bases and organic solvents. Figure 5 shows the spin coating system photographs.

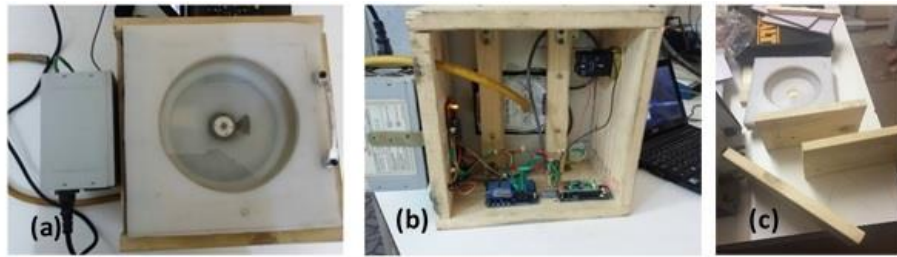


Figure 5. A photo-image of the (a) The spin coating system, (b) Backside of the spin coater where the electronics circuit is fixed, (c) Spin coater while construction

3. RESULTS AND DISCUSSION

In order to evaluate the proposed spin coater performance, the system is used to deposit ZnO thin films on the glass substrates by sol-gel method. The ZnO sol-gel is prepared as follows; Zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$: $ZnAc_2 \cdot 2H_2O$) (0.5 M) was dissolved in a solution consisting of 20 mL isopropanol($(CH_3)_2CHOH$) and 1 g diethanolamine (DEA: $[CH_2(OH)CH_2]_2NH$) at room temperature (300 K). The molar ratio of zinc acetate to DEA was 1:1. At room temperature, the solution was stirred for 1 h to get a clear and transparent solution that was used for spin coating. [21]

To obtain a thin film on a glass substrate by a spin coater, the substrate must be fully dry and completely clean. The $2.5 \times 2.5 \text{ cm}^2$ glass substrates were cleaned before deposition. The cleaning process was carried out on the following steps; the substrates were soaked in the isopropanol sonicated for 2 minutes, immersed in the acetone for 1 minute, rinse and washed with deionized water, then dried. [22]

3.1. Spin Coater in Use

Two groups of samples are used to determine the coating quality, each group of samples has a different set of coating parameters. Spin speed parameter varying from 2000-7000 rpm for the spin time equal to 40 seconds, that for the first group. For the second group, the spin time parameter was changed from 10 to 90 seconds at 4000 rpm. The volume of solution used for each sample is 0.25 ml. All coatings were followed by pre-heating the at 373 K for 10 min and post-heating at 723 K for 1 h in an air-ambient muffle furnace for dried and calcined, respectively. [23] The thickness of each sample was measured using spectroscopic reflectometer system type thickness film probe (TFProbe) from Angstrom Advance Inc.

Figure 6 shows spinning speed versus ZnO thin film thickness coated with the built system. The spinning speed within the range of 2000-7000 rpm, spin time by is equal to 40 seconds. The figure illustrates that the thickness of the membrane decreases with the increase of the spinning speed of the device. The illustrated results show an agreement with previously reported results. [24] At 2000 rpm, the thickness of the thin film is about 400 nm and further increases to 4000 rpm, the thickness reduced to the half (200 nm). When the speed increases to 7000 rpm, the thickness becomes about 115 nm. As the speed increases, the rate of the change in thickness is reduced.

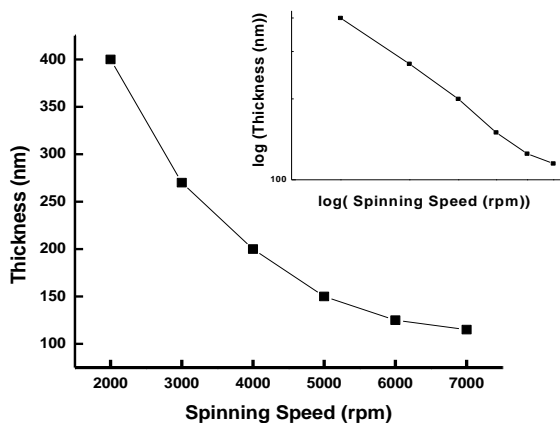


Figure 6. Effect of the spinning speed on ZnO thin film thickness

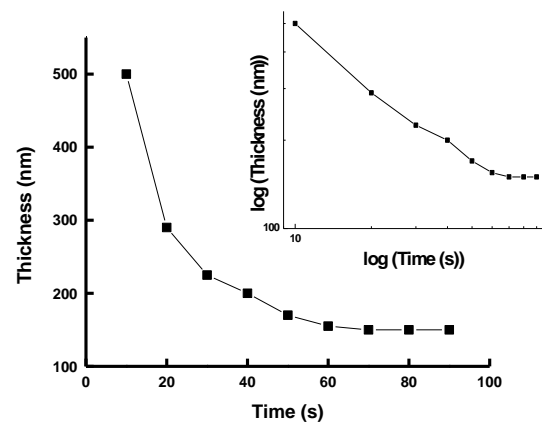


Figure 7. Effect of the spinning speed time on ZnO thin film thickness

It is well known that, the thin film thickness proportion with the evaporation rate of the solvents. There are three possible cases that determine the thickness of thin films:[10] (A) When the solvent does not evaporate, the thickness of the thin film (h) is proportional to the spinning speed (ω) and the spinning time (t) ($h \propto \omega^{-1} t^{-1/2}$), (B) When the solvent evaporates at a constant evaporation rate, the thickness of the thin film is proportional to the speed of rotation ($h \propto \omega^{-2/3}$), (C) When the solvent evaporates at not-constant evaporation rate, the thickness of the thin film is proportional to the square root of spinning speed ($h \propto \omega^{-1/2}$).

Figure 6 demonstrates that the thickness of the membrane decreases with the increases of the spinning speed. From nonlinear fit, by using Origin software version 6, it is found to be the thickness proportional with ω^{-1} and follows a case (A) above, in such case (h) is proportional to the spinning speed ω^{-1} and the spinning time t . The inset of Figure 6, shows the log-log data of Figure 6 to clarify dependencies on ω^{-1} . Figure 7 illustrates the spinning time versus the average thickness at a particular speed of 4000 rpm. At spinning time equal to 40 seconds, the average thin film thickness is 200 nm. When the time is increased to 60 seconds, the film thickness becomes 155 nanometers, further increased to 90 seconds, the thickness becomes 150 nm and the thickness decreases-rate gradually reduces and reaches a specific value. This phenomenon can be due to the viscosity change of the ZnO gel-sol during the coating process. From the nonlinear fit of the Figure 7 curve, it is found to be the thickness proportional with $t^{-0.6}$, which is very close to the case (A) that thickness proportion to $t^{-0.5}$. The inset of Figure 7, shows the log-log data of Figure 7 to clarify dependencies on $t^{-0.6}$. These results are consistent with the previously reported work to deposit thin films obtained by a sol-gel method using commercial coating devices [25].

4. CONCLUSION

We design, implement and characterize a feedback programmable spin coater. This system is built from a commercially available hard drive DC motor, vacuum pump, IR feedback circuit, brushless click carries, microcontroller. In addition, the system is connected to the computer through an interactive user interface designed with the programming languages (Visual Studio.Net). The main feature of this system a wide range of stable accurate multi-step spinning speeds using feedback circuits and PWM technique to overcome the drawbacks of the traditional systems such as speed degradation with utilization. Three different voltage stages have been implemented 5, 7 and 10 V to achieve a wide range and high resolution of the operation speed of spin coater apparatus. ZnO thin films deposited by sol-gel technique on glass substrates produced with the built system. The resulting thin films are uniform and homogenous with accurate ability to control their thickness by high precision controlling of spinning speed and time. As a result, the proposed system is a low-cost, high-efficiency and durable system since the system efficient daily use in our laboratory for about 1 year.

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