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Application of Monitoring Module Three-in-One Microsensor to Real-Time Microscopic Monitoring of Polarizer Sheet in Roll-to-Roll Process

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Abstract: The Roll-to-Roll (R2R) process refers to a high-efficiency, low-cost, continuous production method. The roll material used for processing is a flexible plastic or metal film. In many R2R processes, polarizing films are high-precision products with a high output value. In the production of conventional polarizers, product inspection will only be carried out after the production of the polarizing film is completed. The principal raw material of a polarizer sheet is a hydrophilic polymer, the properties of which may be influenced by water vapor, which degrades its quality. Whether or not the product is impacted can be ascertained by means of a quality inspection, but it must be performed after the process is finished. However, it is already too late when a defective product is detected: the production cost is increased, the schedule is influenced and the delivery date is delayed. The focus of this research was on environmental monitoring of the production drying process oven, but the commercial all-in-one sensors currently on the market cannot tolerate the temperature of the factory's high-temperature oven. In particular, a commercial flow sensor is rarely suited to high-temperature applications. Some are expensive and cannot be widely distributed. Therefore, this study aimed to develop an integrated sensor to measure the internal environment of the drying process oven for the real-time monitoring of a polarizer sheet in the Roll-to-Roll (R2R) process. This study used micro-electro-mechanical systems (MEMS) technology to make a flexible three-in-one (temperature, humidity and flow) micro-sensor. We monitored the temperature, humidity and flow uniformity in a laboratory oven to simulate the environment of the actual factory oven, with the aim to provide data to confirm whether or not a polarizer sheet has dried. Our system can be monitored instantly by Arduino, or even Raspberry Pi 3, to realize the flexible micro-sensor layout and field verification, in order to optimize the R2R process and to enhance the yield and performance of the polarizer sheet process.

Keywords: polarizer sheet; R2R; self-made flexible three-in-one micro-sensor

1. Introduction

The Roll-to-Roll (R2R) process refers to a high-performance, low-cost, continuous production method, and the processed target is a thin and flexible film that is known as soft board. The material of the thin film is a plastic or stainless steel sheet with a thickness of less than 0.1 mm. When the thin film is unwound from the cylindrical feed roll, it is provided with specific functions, or the film surface is processed, and then the film is either rolled into a cylinder or the end product is cut directly. Taking the processing program of pattern molding as an example, the manufacturing method of 'Unwind' → 'Process' → 'Rewind/Cutting' is known as the R2R process.

Choi et al. [1] used Drop-on-Demand (DOD) and electrohydrodynamic (EHD) techniques to print a temperature sensor onto a Polyethylene Terephthalate (PET) flexible substrate for measuring the temperature of any plane or curved surface. Starke et al. [2] used Polyethylene Terephthalate (PET) as a substrate to make a humidity sensor via inkjet printing, and besides the low cost, the pseudo-hysteresis was lower, the gap between the print electrodes was reduced, the capacitance of the sensor was increased and a low relative humidity could be measured. Farahani et al. [3] classified humidity sensors, together with ceramics, organic polymers and composites, as sensing elements, and discussed the effect of ambient temperature, configuration and structure on the sensor. Their findings proved that the price of the thin film sensor was low, and that it had a flexible design and better response characteristics.

A wide variety of temperature sensors are used extensively, including optical fiber temperature sensors [4], thermally sensitive resistors (thermistors), thermocouples and resistance temperature detectors (RTDs) [5]. In recent years, micro-electro-mechanical systems (MEMS) technology has increasingly matured, and the micro-sensors made using this technology have a small volume, a high accuracy, and can be produced in bulk at a low cost. The micro-sensor in this study was fabricated using this method. Currently, micro temperature sensors made by using the MEMS processing technology include thermal resistance temperature sensors, thermopile temperature sensors and thermocouple temperature sensors [6].

Humidity sensors [7] can be classified largely by their humidity-sensitive materials into ceramic, electrolyte and polymer types, each having their own merits and demerits, as well as various applicable temperature and humidity measurement ranges. The humidity-sensitive materials used in general humidity sensors are mostly porous oxides, such as ceramics, graphene [8], nano-structured porous silicon [9], carbon nanotubes [10], Al_2O_3 [11], TiO_2-nanowires [12] and $BaTiO_3$ [13]. Ceramic humidity sensors have a higher operating temperature and a stable structure, but the water molecules are polar molecules, which are very likely to undergo chemical adsorption onto the oxide that is on the ceramic surface, so the sensor cannot be re-used until it is heated to 400 °C. Therefore, they were deemed not applicable to this study. Electrolyte humidity sensors are classified into solid electrolyte and liquid electrolyte types, according to whether dissociation of water molecules is required or not. The solid electrolytes can conduct electricity without the dissociation of water molecules. When the liquid electrolytes are dissolved in water, they are affected by the polarity of the water molecules, so they can be dissociated into mobile cations and anions. The concentration of the electrolyte solution is related to the conductivity of the ions, and it has a linear relationship with the ambient humidity at a constant temperature. This type of sensor has a shorter lifetime, a slower response and a relatively low working temperature, so it cannot be applied to the measurement of humidity at high temperatures or used in a long-term working environment.

The micro-flow sensor was developed by using MEMS technology in 1980. It is characterized by its low power consumption, high precision, small size and high sensitivity to low flow rates [14]. Generally, there are thermal flow sensors [15] and non-thermal flow sensors. Currently, a great variety of micro-flow sensors are being developed using MEMS technology. Thermal micro-flow sensors have become the mainstream micro-flow sensor research products due to their simple structures and easy processes, as well as for their drive- and signal-output circuit designs, and they are now commercially available [16].

The wrinkles on the edge of polarizing film may be caused by the oven baking process or during the subsequent drying process, if the temperature is uneven. Almost all production lines will involve a high temperature oven at the end of the process. Therefore, in order to achieve real-time monitoring of some of the physical conditions inside the oven, we developed a flexible three-in-one (temperature, humidity, flow) micro-sensor to measure these three physical quantities.

During this study we collected and compiled the required data from the literature. We also compared and analyzed the specifications of commercial sensors against the self-developed flexible three-in-one (temperature, humidity and flow) micro-sensor. The flexible three-in-one micro-sensor was made by using MEMS technology to monitor whether or not the temperature, humidity and flow of the oven were abnormal, and to confirm whether or not the polarizer sheet had dried, so as to guarantee the outputs of the process.

The main steps of the polarizing film manufacturing process include dyeing, stretching, lamination and drying. The first step is to produce films with polarizing properties. The hydrophilic PVA film is swelled by immersion in water, and then immersed in a dichroic dye solution. Dichroic dyes are usually solutions of iodine and potassium iodide. Afterwards, the dyed film is stretched to align the dichroic dyes. The higher the degree of order, the better the optical properties of the resulting polarizing film. The stretched film is brittle and easily cracked along the stretching direction after drying, and its raw material is a hydrophilic polymer film, which is easily affected by water vapor. Therefore, it needs to be laminated with a protective film material to provide support and to block water vapor. The selected protective film material is usually triacetate cellulose (TAC) film, which is soaked in an alkaline aqueous solution to convert the carboxylic acid groups on the surface into hydroxyl groups, and then bonded to the polarizing film layer with an aqueous adhesive. For TAC films used in close proximity to a panel, products with specific retardation compensation values can be used to match the optical properties of different panels. The outermost layer of the TAC film can include additional functional coating products to impart anti-glare, anti-scratch and other functions to the surface. Finally, self-adhesive pressure-sensitive adhesive is added to make the polarizer stick to the panel glass. During polarizer manufacturing, pressure-sensitive adhesives are typically pre-coated on polyethylene terephthalate (PET) separators. On film, it is laminated roll-to-roll with polarizers, so before attaching the polarizer to the panel, a protective film made of PET is used to protect the surface of the polarizer.

2. Sensor Process and Principle

2.1. Sensing Principle of the Micro-Temperature Sensor

The base material of this type of sensor is a metal material. In MEMS process technology, this manufacturing method involves simple metal film deposition. Only the deposition of a layer of metal film is required to complete the production of the sensor. The thickness of the film is 50 μm. In order to take advantage of the increase in the transmission temperature of the metal, its resistance can also be measured from its extended characteristics, and platinum or gold are usually used as the metal film material.

Under our existing experimental laboratory conditions, it is most feasible to make resistant temperature sensors (resistant temperature detectors). However, as the compatibility and cost of the process was a consideration, since the temperature of the process and the price of platinum are higher than that for gold, we constructed a micro-temperature sensor, and the selected material was gold (Au) [17].

The sensing principle of a micro-temperature sensor is that when the ambient temperature rises, the resistivity increases with the temperature. As Au has a positive temperature coefficient (PTC), which results from the "Temperature Coefficient of Resistance" (TCR) of the conductor, this is defined in Equation (1).

$$\alpha = \frac{1}{\rho_0}\frac{\Delta\rho}{\Delta T} \tag{1}$$

where $\Delta\rho$ ($\Delta\rho = \rho - \rho_0$) is the resistance change rate between ΔT ($\Delta T = T - T_0$). According to the standard metal long straight conductor (2), the resistance is proportional to the resistivity, and the resistance change is obtained per Equation (3).

$$R = \rho\frac{L}{A} \tag{2}$$

$$R = R_0[1 + \alpha(T - T_0)] \tag{3}$$

where R_0 is the resistance at T_0. Equation (3) can be rewritten as Equation (4).

$$\alpha = \frac{R - R_0}{R_0(\Delta T)} \quad (4)$$

The physical meaning of α is the sensitivity of the micro-temperature sensor (1/°C).

2.2. Sensing Principle of the Micro-Humidity Sensor

The electrode form of the capacitive micro-humidity sensor used in this study was an interdigitated electrode structure. In this type, there is a humidity sensitive thin film above the electrode. When the water vapor absorbed by the thin humidity-sensitive film increases, the dielectric constant increases with the ambient humidity [18]. A miniature humidity sensor was developed. The upper and lower electrodes were designed with parallel holes, and the intermediate dielectric layer was made of polyimide material. It was found that the thinner the dielectric layer, the higher the sensitivity of the humidity sensor [19].

The humidity-sensitive material of this type of humidity sensor is usually a hydrophilic polymer, or a polymer with a charged polar group, such as polystyrene sulfonate, polyvinylpyridine (PVP), polytetrafluoroethylene (PTFE) or a material composed of monomers with ionic bonds. This is because after the polymer has adsorbed water molecules, the dissociation and migration of a charge reduces the impedance of the sensor; the electrical conductivity of ions increases with the ionic mobility and charge carrier, and the variance in impedance is linearly related to the change in relative humidity.

2.3. Sensing Principle of the Micro-Flow Sensor

Micro-electro-mechanical systems (MEMS) technology has been used to develop several types of flowmeters that exploit thermal, Coriolis, ultrasonic, and mechanical flow effects [20]. Among the various flow sensors, the thermal flow sensor is the most common, due to its simplicity of structure and electrical readout [21].

The sensing principle of a hot-wire micro-flow sensor is that the flow is measured using the positive correlation between the heat consumption rate of a heater and the fluid velocity. The structure of the hot-wire micro-flow sensor is based on a heater that forms a stable temperature field; when it is put in the flow field, the temperature field generated by the heater varies with the forced heat convection of the fluid. The resistance value of the heater decreases as the heat that is carried away increases [22].

2.4. Process Development of the Flexible Three-in-One Micro-Sensor

Surface micro-machining technology is used in the production process for flexible three-in-one micro-sensors. The process comprises deposition, lithography and wet etching steps. The fabrication process, entity and optical micrograph are shown in Figures 1 and 2.

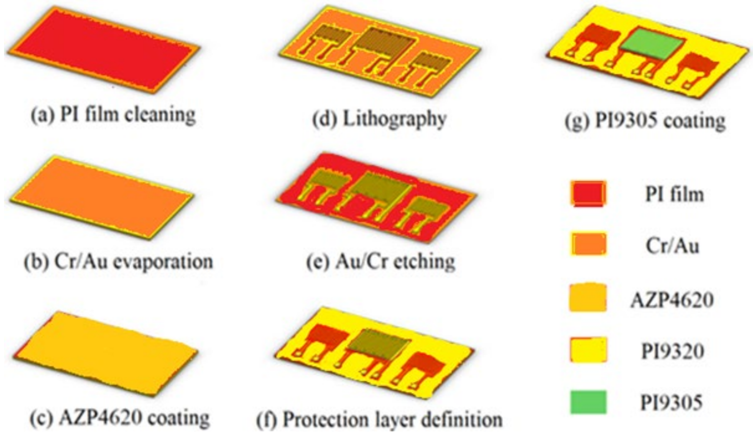

Figure 1. Process chart of a flexible three-in-one micro-sensor. (**a**) the PI (polyimide) substrate was cleaned with an organic solution, such as acetone and methanol, and then the residual methanol, surface dust, and residual oil and fat were removed using DI water, so as to enhance the adhesive ability of thin film metal, with a 0.1 Å/s deposition rate for evaporation; (**b**) the Cr was evaporated by using an E-beam evaporator as the adhesion layer, and the Au was evaporated as the sensing layer; (**c**) In this study, the most common and stable positive photoresist, AZ® P4620, was used to define the circuit pattern structure and wet etching mask, and it was coated by a spin coater; (**d**) the pattern of the micro-temperature, humidity and flow sensor was defined using a photolithography process; (**e**) the pattern was transferred to the metal film of Cr and Au by wet etching; and (**f**,**g**) PI9305 coating was added as a protective layer, the sensing areas and pins were defined using the photolithography process, and the production of a flexible three-in-one micro-sensor was complete.

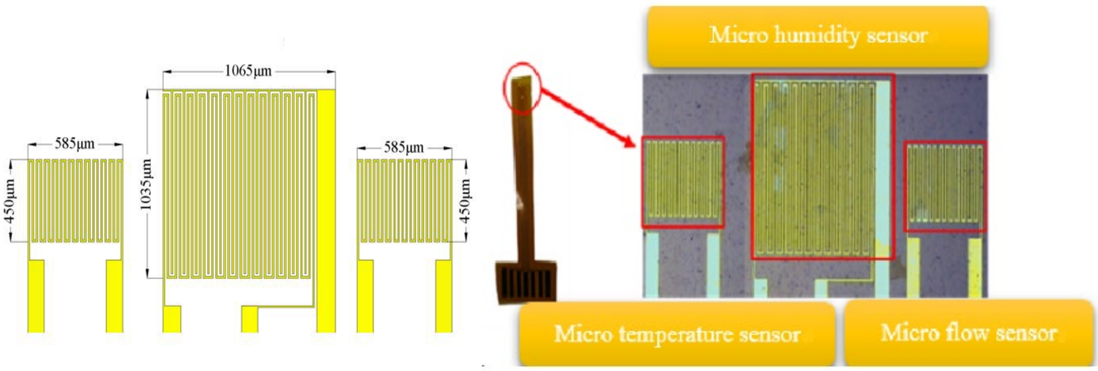

Figure 2. Entity and optical micrograph of a flexible three-in-one micro-sensor.

The temperature and flow micro-sensors used in this research were all wire-wound structures. The process of making the wire-wound structure was the key to the outcome of the research process. In order to improve the quality and yield of the process, the line width of the temperature and flow micro-sensor in this study was 15 μm, the wire-wound interval was increased from the original 10 μm to 15 μm, and the overall process yield was able reach more than 90%. In this way, the parameters of the process were wider and easier to master.

2.4.1. Polyimide Film Cleaning

Before starting this process, it was noted that the cleanliness of the substrate surface will significantly affect the subsequent process, and may even cause structural damage. Therefore, the film must be soaked in an organic solvent of sulfuric acid, methanol and isopropanol to clean it in advance, and finally, a nitrogen gun must be used to remove the volatile organic solvent, isopropanol. It is then put into the electron beam evaporator.

In order to increase the adhesion of the vapor-deposited metal on the substrate, the polyimide film (Corona) was replaced in this study. When the ions are ejected from the nozzle, they destroy the molecular structure of the film surface through electric shock and penetration, causing oxidation and distortion of the surface molecules, transforming it into a rough film, and thus increasing the adhesion ability of the material surface.

2.4.2. Thin Film Deposition (Chromium and Gold)

In this study, a physical vapor deposition (PVD) electron beam evaporation machine with a fast film formation speed and high efficiency was used to deposit the thin metal films. The selected electron beam evaporation machine brand model was EBS-500 (Junsun Technologies Company), which has the advantages of fast film deposition and a high single-shot yield. The principle of an electron beam evaporator is that the electric current is passed into the tungsten wire to generate high heat, so that the outer electron kinetic energy is greater than the bound energy and overflow; the electron beam is directed by the magnetic field to hit the target in the crucible in order to heat the target to melting point, which then evaporates and deposits upward onto the surface of the substrate.

In order to improve the yield of the flexible integrated micro-sensor in this study, a deposition rate of 0.1 Å/s was maintained throughout the vapor deposition process to ensure the denseness of the coating. The process first vaporizes a 100 Å thick chromium (Chrome, Cr) adhesion layer between the substrate and the gold, and then deposits 1000 Å gold as the main construct of the flexible integrated micro-sensor material of the structure.

2.5. Evaluation and Test of the Commercial Temperature and Humidity Sensors

As the raw material of the polarizer sheet is a hydrophilic polymer film, its properties are likely to be influenced by water vapor, and therefore monitoring of the temperature and humidity is very important. Temperature and humidity sensors were used to monitor whether the temperature inside the oven was non-uniform and whether the humidity was too high, and to confirm whether the polarizer sheet had dried, so as to guarantee the output of the polarizer sheet process and to enhance its performance. Therefore, in this study we collated the required data from the literature. We also compared and analyzed the specifications of the commercial sensor against the self-developed flexible three-in-one (temperature, humidity and flow) micro-sensor.

After evaluation of various commercial sensors, Sensirion SHT21 commercial temperature and humidity sensors were selected. The temperature sensing range is −40 °C~125 °C and the temperature accuracy is ±0.3 °C. The humidity measuring range is 0%~100% and the humidity accuracy is ±2%. For sensing the temperature and humidity inside the oven, the sensor was placed in the oven through a hole. After a Gerber graph of the circuit board meeting the Sensirion SHT21 specification was drawn, and the PCB was cleaned, Sensirion SHT21 commercial temperature and humidity sensors were printed on the PCB. Finally, they were connected to cables that were tolerant to temperatures up to 125 °C, so that the signals could be exported to a Bluetooth wireless module and sent out. The test module is shown in Figure 3. The commercial SHT21 wireless temperature and humidity sensors use high temperature-resistant wire as the signal transmission line between the PCB and Arduino development board, and the data are read by Arduino software to calibrate the constant temperature and humidity. The temperature correction range of the micro-temperature sensor was from 20 to 105 °C, the humidity was 100%RH and the interval unit used for completing the temperature correction curve was 5 °C. However, in order to ensure that the temperature and humidity are evenly spread throughout the large cavity of the test equipment, we waited a few minutes after the temperature and humidity had stabilized, as they needed to be as close as possible to the temperature and humidity settings of the constant temperature and humidity equipment. The test data are shown in Figures 4 and 5. According to the experience of the partner manufacturer (BenQ Materials CO., LTD, Taoyuan, Taiwan), an oven maintained at 110 °C results in the best operating temperature. When the oven temperature is maintained at 110 °C, a signal is received every 10 s, and then any defective products with high deviation can be rejected. It was found that there were some slight differences, compared to the wired temperature and humidity sensors originally used in the production line. Therefore, to avoid errors in future, we plan to send related units for unified calibration. The temperature of the R2R process can be up to 120 °C. As the flow sensors of the commercially-available three-in-one (temperature, humidity and flow) sensors can only work at temperatures less than 65 °C, this study used MEMS technology to complete the self-made flexible three-in-one micro-sensor.

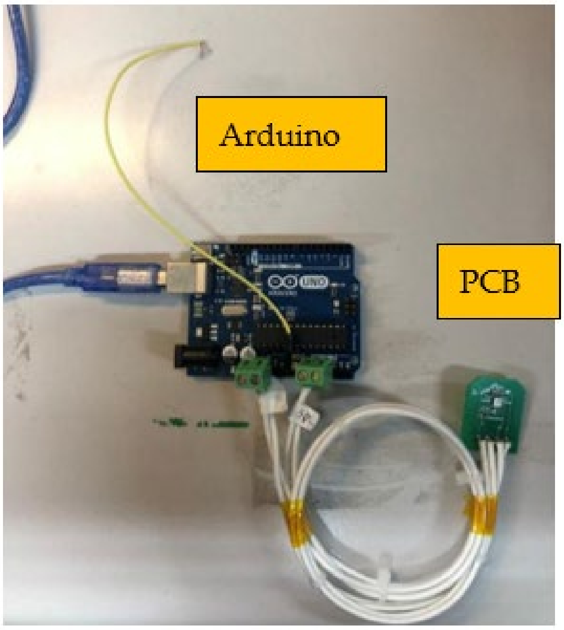

Figure 3. Stereogram of temperature and humidity test module.

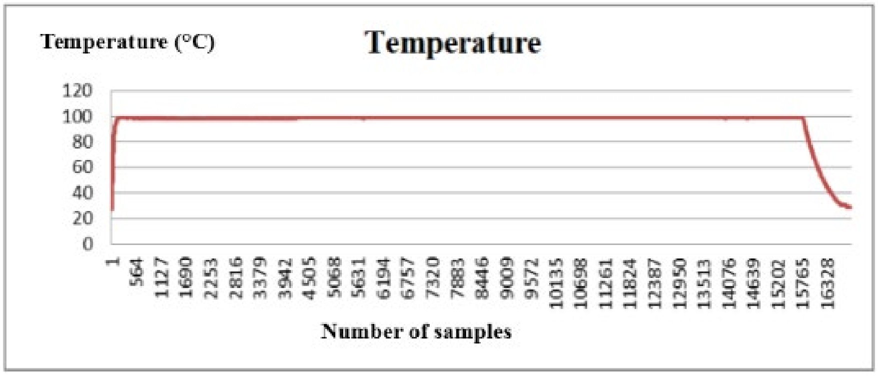

Figure 4. Diagram of temperature sensor test data.

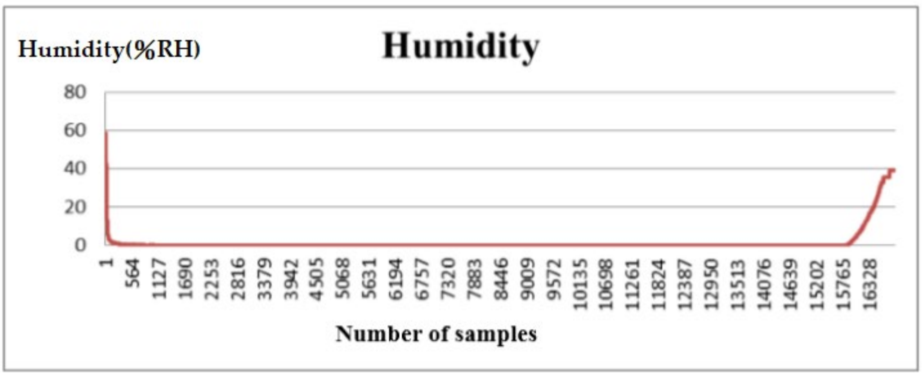

Figure 5. Diagram of humidity sensor test data.

2.6. Polarizing Film

During the oven-baking part of the drying process, an uneven temperature leads to wrinkles. Almost all production lines involve a high-temperature oven at the end of the process. Therefore, in order to instantly monitor some of the physical conditions inside the oven, various types of functional sensors, such as temperature, humidity and gas flow sensors, were used.

3. Correction of Self-Made Flexible Three-in-One Micro-Sensors

After an integrated micro-sensor is manufactured, it is cut, the signal line is stretched, and the temperature, humidity and flow micro-sensors are calibrated to verify their reliability. After confirming that everything is functioning normally, the wireless sensor software writing and subsequent packaging are completed. The following is a detailed introduction to the cutting and wiring, reliability testing and calibration methods, steps and details for the manufacture of the integrated micro-sensor.

3.1. Cutting and Wiring of the Integrated Micro-Sensor

First, the integrated micro-sensor was manually cut to a minimum size, close to the edge of the sensing structure, then it was glued to the ceramic substrate. Conductive copper foil tape and conductive silver glue were then used in signal wire welding to connect the signal of the flexible integrated micro-sensor to the ceramic substrate. The integrated micro-sensor, after the signal line was soldered, is shown in Figure 6.

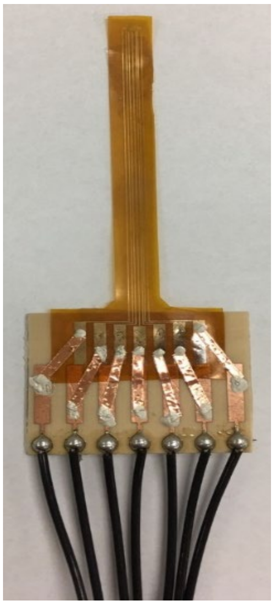

Figure 6. The actual product picture of the integrated micro-sensor after the signal line was soldered.

3.2. Correction of the Micro-Temperature Sensor

To ensure the simulated correction environment was close to that which occurs inside an oven, this study used program-controlled constant temperature and humidity test equipment (Hung Ta HT-8045A Environmental Chamber) as a reference for the correction environment. In order for the results to be applicable to the production line oven of the partner manufacturer, the oven used for the experimental test was the same size. Because the chamber of the test equipment was large, and in order to make sure that the temperature and humidity were uniformly distributed throughout the chamber, it was necessary to wait for about 10 min after the temperature and humidity were stable, so that the results were as close as possible to the equipment's own temperature and humidity sensors. The signal line was connected to the NI PXI 2575 data capture equipment to correct the temperature of the micro-temperature sensor. The temperature correction range of the micro-temperature sensor was 20 °C to 105 °C, and the interval was 5 °C. The signals were captured and averaged at a steady temperature over one minute, and they were measured three times. The results were transferred into a curve diagram. The 'temperature-resistivity' curve for the micro-temperature sensor was dimensionless and presented a high degree of linearity, as shown in Figure 7.

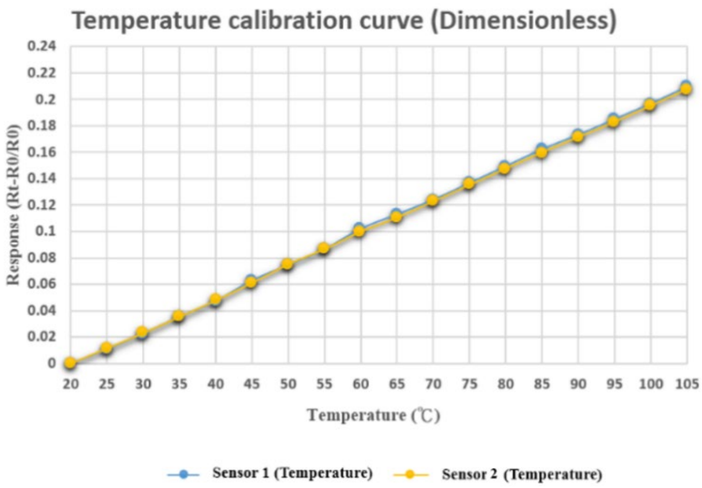

Figure 7. Correction curve of the micro-temperature sensor.

3.2.1. Micro-Humidity Sensor Correction

The humidity correction was also tested using the program-controlled constant temperature and humidity test equipment. The humidity correction range was set at 20%RH to 98%RH, and the data were recorded at intervals of 5%RH. However, as the capacitance signal of humidity varies at different temperatures, and as it changes slightly during humidification and dehumidification, the humidity was corrected by measuring the capacitance during humidification and dehumidification from 20%RH to 98%RH at different temperatures. During the process to realize the humidity correction, the temperature range was set at 20 °C to 85 °C and the temperature rise set at intervals of 5 °C. The humidity range was set at 20%RH to 98%RH, and the interval at 5%RH. The average capacitance signal over one minute, at a steady temperature and humidity, was recorded by the NI PXI 2575 data acquisition unit. The measurements were performed three times, the average was calculated, and the results were fitted to a curve. The 'relative humidity-capacitance value' curve for the micro-humidity sensor was dimensionless, as shown in Figure 8.

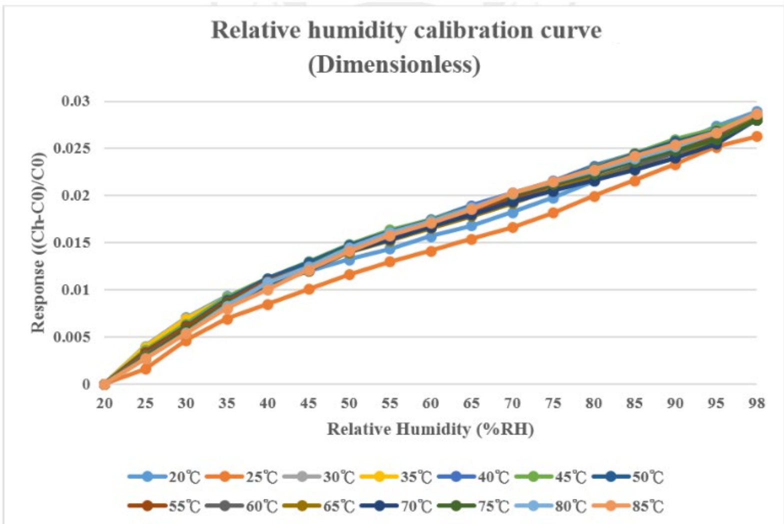

Figure 8. Correction curve of the micro-humidity sensor.

3.2.2. Micro-Flow Sensor Correction

The micro-flow sensor was corrected by the stable and variable flow input provided by an 850E fuel cell testing machine.

To proceed with the correction of the micro-flow sensor, it was sandwiched between two bipolar plates and then aligned with the runner position. An Arduino Uno Rev 3 development board was used as the power supply, and NI PXI 2575 data capture equipment was cascaded between the power supply and the hot-wire micro flow sensor to measure the current variation values. The power supply supplies a constant voltage, so that the micro-flow sensor generates a stable temperature field, and air is admitted for correction. During flow correction, the range of Sensor 1 was set at 0 to 3000 cc/min, the interval was 300 cc/min, and the average current signal was recorded over one minute at a stable flow. The range of Sensor 2 was set at 3000 to 0 cc/min, the interval was 300 cc/min, and the average current signal was recorded over one minute at a stable flow. The measurements were taken three times and the average was calculated. The 'flow-current' curve for the micro-flow sensor was dimensionless, as shown in Figure 9. The power consumption was 0.00864 W, and the sensitivity was 0.0003 mA/(mL/min). The specifications of the three-in-one flexible micro-sensor are shown in Table 1 below.

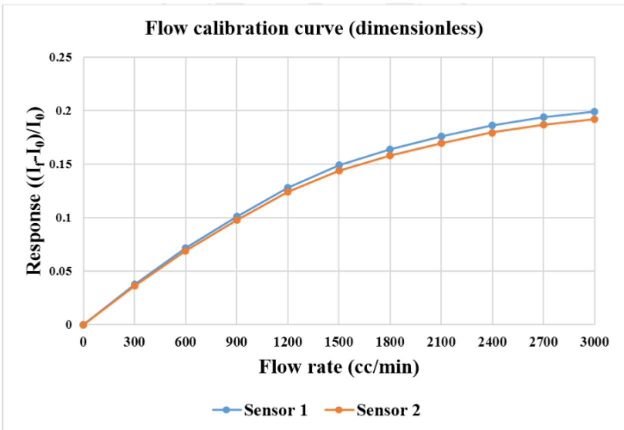

Figure 9. Correction curve of the micro-flow sensor.

Table 1. Specifications of the three-in-one flexible micro-sensor.

Name	Three-in-One Flexible Micro-Sensor	
	Micro-electro-mechanical systems (MEMS) were utilized to develop three-in-one flexible micro-sensors, which integrated a micro-temperature, flow and humidity sensor on a 50 µm thick polyimide film.	
Specifications	Flexible micro-temperature sensor: • Size: 450 µm × 585 µm × 50 µm • Operating range: −40 °C~125 °C • Accuracy: ±0.3 °C (depends on measurement equipment) • Response time: 1 ms • Sensitivity: 2 × 10^{-3} °C^{-1}	Flexible micro-flow sensor: • Size: 450 µm × 585 µm × 50 µm • Operating range: 0~30 L/min • Accuracy: ≤0.1 mL/min (depends on measurement equipment) • Response time: 1 ms
	Flexible micro-humidity sensor: • Size: 1035 µm × 1065 µm × 50 µm • Operating range: 0%RH~100%RH • Accuracy: ±3%RH (depends on measurement equipment) • Response time: ≤15 ms	

4. Results and Discussion

This study used MEMS technology to integrate micro-temperature, humidity and flow sensors on a 50 µm thick Polyimide (PI) film substrate, and it used PI (Fujifilm Durimide® LTC 9320, Hsin-Chu, Taiwan) that was resistant to electrochemical corrosion and acid as a protective layer. This self-made flexible three-in-one micro-sensor had three functions; namely, it could monitor the temperature, humidity and flow.

4.1. Monitoring Data and a Comparison of a Self-Made Flexible Three-in-One Micro-Sensor and a Commercial Sensor

4.1.1. Monitoring Data and Comparison of Temperature Sensors

The temperature changes in the oven are shown in Figure 10. They were measured over the period of a gradual rise from room temperature (25 °C) to 110 °C, and then a natural drop from 110 °C back to room temperature (25 °C). The temperature measurement curves of the self-made and commercial temperature sensors were recorded and compared, and the results are shown in Figure 11. It can be observed in Figure 11 that the measurements obtained from the self-made and commercial temperature sensors were a little delayed compared to the oven thermometer, but the numerical differences between the self-made temperature sensor and commercial temperature sensor were almost the same. Therefore, it was determined that the self-made temperature sensor had a considerable accuracy in temperature measurement.

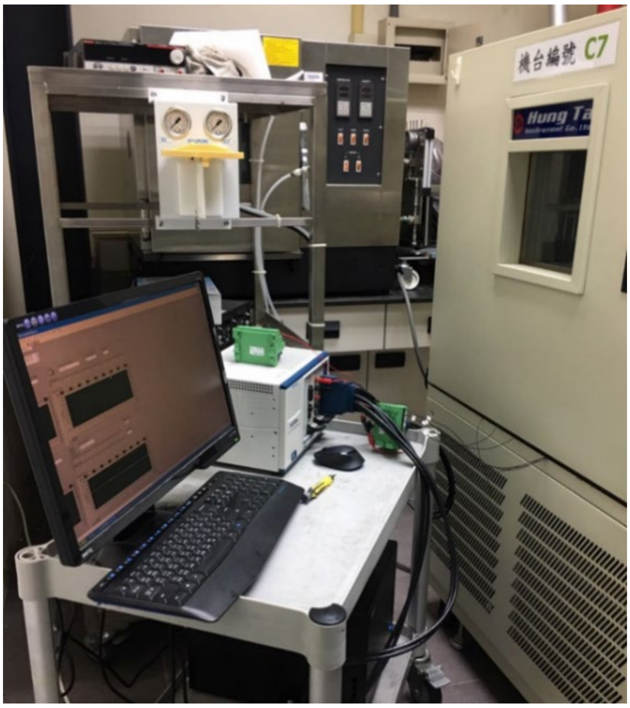

Figure 10. The three-in-one sensor installed in the oven.

4.1.2. Monitoring Data and Comparison of Humidity Sensors

The humidity measurement curves of the self-made and commercial humidity sensors were recorded and compared, and the results are shown in Figure 12. It can be observed in Figure 12 that there are small errors between the humidity values measured by the self-made humidity sensor and the commercial sensor; this was attributed to be because the sensitivity of the selected material was not sensitive as expected, so there was a hysteresis in the humidity rise/drop.

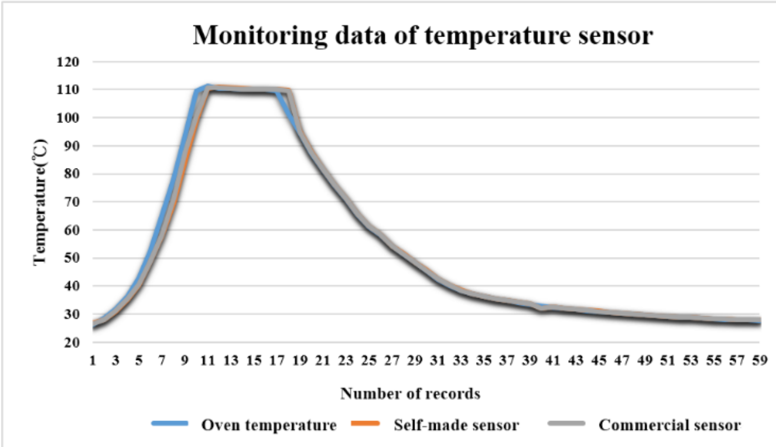

Figure 11. Temperature sensor monitoring data.

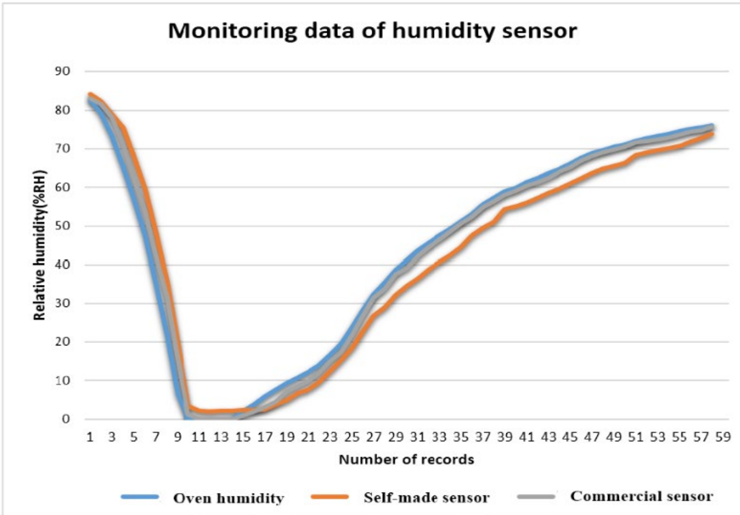

Figure 12. Humidity sensor monitoring data.

4.2. Improving the Self-Made Integrated Sensor Monitoring Module

Although the self-made integrated sensor could perform basic monitoring, there are still many flaws and imperfections that need to be addressed. In the humidity sensor component, the material of the dielectric layer needs to be strengthened, and it is necessary to find a better humidity-sensitive material, in order to make its response more immediate. In the monitoring module component, there is currently only a preliminary and simple experimental structure. The combination of the development board and additional accessories (a Bluetooth board, an SD card, a power supply, etc.) is a little cumbersome. In the future, it will be gradually replaced by a smaller, functionally-specific board, so that multiple points can be arranged on a production line.

5. Conclusions

The self-made flexible three-in-one micro-sensor could successfully extract the internal temperature, humidity and flow information from a polarizing film manufacturing process oven using the self-made wireless monitoring module, without influencing the polarizing film process environment. We demonstrated that it can be used to observe and evaluate whether the internal temperature, humidity and flow control settings, and the heat uniformity of the oven, need modification or improvement, in order to reduce defects in the polarizing film sustained during the oven process, and thus to increase the yield.

The focus of this research was on the environmental monitoring of the oven drying process, as the commercial all-in-one sensors currently on the market cannot tolerate the temperature of the factory's high-temperature oven. In particular, commercial flow sensors rarely have high-temperature applications. Some are expensive and cannot be widely distributed. Therefore, this research aimed to develop an integrated sensor to measure the internal environment of the oven used in the drying process.

This flexible integrated micro-sensor had four advantages, namely, its thinness, its small structure area, its high sensitivity and its real-time measurement.

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