Sensors and Materials, Vol. 28, No. 1 (2016) 33–41
MYU Tokyo

S & M 1154

Thermal Shock and Resistance Behavior Relationship of Bed Occupancy Sensor

Chuan-Shih Wu,[1,3] Sheng-Yao Lin,[2,3*] and Tsair-Rong Chen[1]

[1]Department of Electrical Engineering, National Changhua University of Education,
No. 1, Jin-De Road, Changhua, Taiwan, R.O.C.
[2]Department of Mechanical Engineering, Lunghwa of University Science and Technology,
No. 300, Sec. 1, Wanshou Rd., Guishan District, Taoyuan, Taiwan, R.O.C.
[3]Solid Year Company Limited, No. 94, Baozhong Rd., Xindian District, New Taipei City, Taiwan, R.O.C.

(Received April 9, 2015; accepted September 10, 2015)

Keywords: care receiver, sensor pad, thermal shock

Ageing populations are driving demand for long-term healthcare. In this study, we developed a bed occupancy sensor, which works by generating a small electrical current when a load is applied to a “sensor pad”, which then triggers an external electronic control device. When the load is removed, the circuit is broken, and a signal is sent to healthcare providers, alerting them that the patient has gotten out of bed. The connection between the sensing device and the nursing station could also be used to provide an emergency call functionality. We then evaluated the reliability of the sensor pads by applying thermal shocks and repeated loading. Changes in electrical resistance were used to determine the relationship between the three. We then observed variations of the surface state using scanning electron microscopy and atomic force microscopy, as a reference for future oil ink smear adjustments. Future research could focus on other functions, such as the detection of pressure distribution, the measurement of respiratory signals, and the assessment of sleep quality. Automating the monitoring of these aspects of care could help to reduce the pressure on healthcare personnel and provide additional patient data in cases of home care.

1. Introduction

In 2013, the World Health Organization announced that the global proportion of elderly individuals (65 to 80 years of age) exceeded 11.7% of the general population. It is estimated that by 2050, this figure will reach 21.1% (2 billion individuals). In addition, the number of individuals exceeding the age of 80 is expected to reach 19%. The current workforce in long-term healthcare is insufficient to meet this demand; therefore, efforts should be made to direct more attention to home care services. The aim of this research is to develop the means to ensure a healthy, comfortable, and safe existence for the elderly, despite dwindling healthcare resources.

In this study, we developed a sensor pad that reacts to a patient’s getting into or out of bed. Immediate knowledge as to the whereabouts and status of an elderly charge can reduce the burden on healthcare workers and give families peace of mind with regard to the well-being of elderly family members. Our aim in the design of the device was to ensure outstanding functionality at a reasonable cost without sacrificing comfort or convenience. In this paper, we outline the working principles of the device as well as the electrical properties, such as the relationship between load

*Corresponding author: e-mail: sa29@ms41.hinet.net

ISSN 0914-4935

and resistance. Actual measured values were used to determine the performance and stability of the sensor pad.

2. Literature Review

Numerous technologies for sensing the physical activity of patients without the need for direct surveillance have been developed. However, many of these monitoring systems require the construction of large-scale testing equipment in a laboratory environment, owing to the difficulties involved in implementing studies in homes or the sleep environment. De Rossi *et al.*[1] coated fabric using conductive polymers with piezoresistive materials of carbon-filled rubber to produce a wearable device capable of measuring and recording data related to the posture and movement of the wearer. Pacelli *et al.*[2] employed piezoresistive cloth or conductive fabric as electrodes, which were then integrated into clothing to measure physiological signals and body posture. This sensing technology is suitable for long-term measurement, as it has proven almost imperceptible to the user, making it very comfortable to wear. Lokavee *et al.*[3] used force-sensitive resistors arranged in an array for the fabrication of thick polymer films to be placed on pillows to provide signals related to sleep posture and cardiopulmonary status.

Most previous devices have only a layer of silver or graphite coated on a polyethylene terephthalate (PET) film surface. In this study, we coated a layer of silver on the PET surface, and then coated it with a layer of graphite. We also developed a coating technology that provides greater sensitivity in the detection of pressure with superior deformability than that achieved in previous sensor pad designs. These advancements are expected to extend the service life of the sensor pad from 3 months to 6–8 months.

3. Working Principle and Structure of Proposed Sensor Pad

The proposed pressure sensor pad was designed to monitor the state of care receivers when getting into or out of bed as well as their physical activity during sleep. External load causes internal changes in the contacts of the sensor unit, which alter the electrical characteristics of the sensor pad. The sensor pad in this study uses an intermediate layer of elastic material (the thickness of the main body measures 3.5 mm) to which is attached a proprietary conductive film developed by Solid Year Co., Ltd., as well as an outer layer of leather. This creates the sandwich structure[4] illustrated in Fig. 1.

Respectively shown in Figs. 2(a) and 2(b) are an image of a completed bed occupancy sensor and a sensor pad with the following dimensions: length of 80 cm, width of 30 cm, and thickness of 4 mm.

As shown in Fig. 3, a layer of high-purity silver paste is first printed on the PET film, which is then covered with a graphite layer as a protective cover. The total thickness is controlled to within

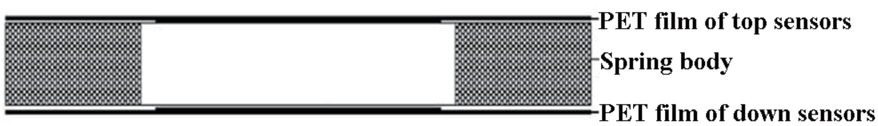
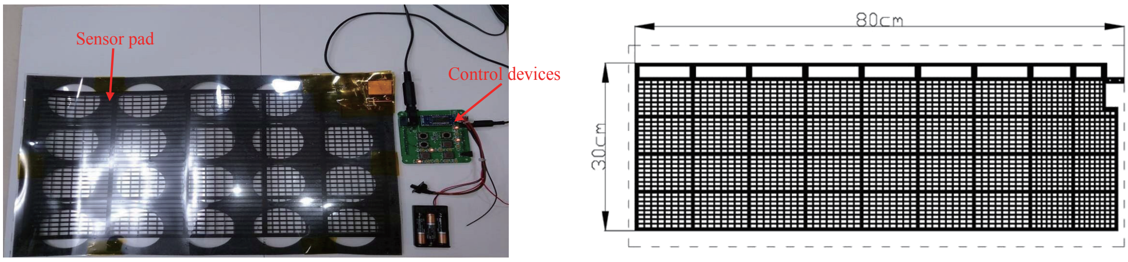


Fig. 1. Sandwich structure of sensor pad.



(a) (b)

Fig. 2. (Color online) (a) Sensor pad and control device. (b) The designed figure was created by a screen-printing method on the PET film.

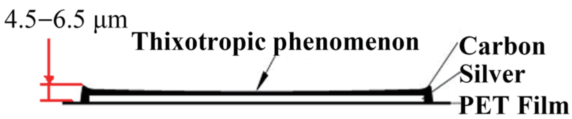


Fig. 3. (Color online) Drying of the oil ink resulted in the thixotropic phenomenon in the sensor film.

4.5–6.5 μm, as shown in Fig. 3. When the oil ink dries (underlying silver layer, overlying graphite coating), the center of the printed area sinks slightly in a process referred to as the "thixotropic phenomenon".[(5)] The average resistance of the oil ink is controlled to below 300 Ω/m. This inexpensive fabrication process takes advantage of the high-speed conduction behavior and toughness of silver as well as the protective properties of graphite in preventing oxidation and resisting physical damage. As shown in Fig. 3, this study used the high-speed transmission capacity of silver atoms to accelerate the responsiveness of the bed occupancy sensor pad.

As shown in Fig. 1, signals from the sensor pad are transmitted via a cable used to control the bed occupancy sensor, whereas the other wire is used as an output from the bed occupancy sensor to capture the signal. A cable (two wires/outside diameter 26 AWG) is soldered to the sensing film of the soft conductive plate with the connection covered using insulating tape to prevent the upper film from making contact with the lower layer under non-loaded conditions. This is particularly important in cases where moisture buildup leads to conditions conducive to free electron conduction.

As shown in Fig. 4, the voltage divider circuit remains open under unloaded conditions and closes when pressure is applied to the sensor pad. The resistance value of the sensor pad varies according to the applied load as well as the area over which pressure is applied.

4. Thermal Shock, Applied Load, and Changes in Electrical Characteristics

Experiments were performed to characterize the relationships among changes in thermal shock, applied load, and resistance in the sensor pad. Finally, we investigated the stability of the sensor pad under various conditions of thermal shock and repeated loading. The purpose of these experiments was to verify the functionality of the sensor pad after prolonged usage and identify manufacturing methods that could be used to increase the lifespan of the sensor pad.

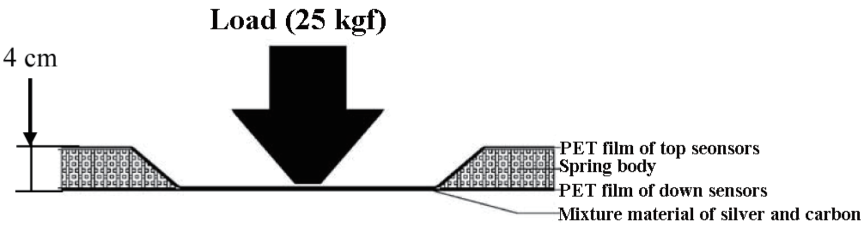


Fig. 4. Load state (25 kgf) formation of sensor pad pathway state.

This study assembled a database based on measurements of the surface area of the body. Our findings indicate that among individuals between 20 and 70 years of age, the average body length, shoulder width, and chest thickness are 173 ± 20 cm, 55 ± 20 cm, and 42 ± 20 mm, respectively. The average weight of care receivers ranges between 45 and 100 kg. Based on experimental data and demand conversion the force range per unit area of the sensor pad obtained was 27.88 g/cm^2 ± 10 cm. Subsequent experiments were performed using a force of approximately 27.88 g/cm^2.

Figure 5 illustrates the process used in the experiments. The sensor pad was placed flat on a platform, and the two wires at the outlet end were connected to the output terminal of the programmable interface controller (PIC) single-chip control board at the back-end of the sensing device, where they captured resistance signals and the input terminal of a microcomputer unit (MCU) single-chip controller. The voltage dividing circuit yields the reaction voltage and resistance values of the sensor pad. The MCU single-chip controller is responsible for providing the sensor pad operating voltage of +3.3 V as well as supplying warning prompts and activity status of the patient. The input end of the PIC single-chip control board returns the working voltage sensed by the sensor, whereas the PIC single-chip provides signal processing and continuously converts analog signals to digital, which are then displayed and stored on a personal computer.

To mitigate the effects of uneven pressure distribution, we used a set of pressure control sources (the weight load can be controlled to 5–50 kgf) in conjunction with a force balance and compensation spring. We designed a set of cylindrical plastic hammers to be similar in surface area to the 100 cm^2 distribution of a typical posterior. The pressure control source can effectively adjust the weight freely and sort out the problem of uneven pressure.

4.1 Relationship between thermal shock and the rate of resistance change

Subjecting a sensor pad to a given force over a fixed area reveals a relationship between the load and the resulting resistance value. We continuously recorded the resistance values under various temperatures (thermal shock test), while maintaining a uniform load and fixed contact area. The presented results are the average values obtained after performing the experiment five times.

Figure 6 presents the thermal shock curve, which represents the relationship between repeated loads on the sensor pad and the rate of change in the resistance value under thermal shock following prolonged periods of use. We evaluated the reliability of the oil ink in the sensor pad as an indicator of its ability to withstand repeated loads over a prolonged period (36 h), during which the temperature was varied considerably. The changes in temperature started with a drop from 25 to −20 °C for a period of time, and then a gradual increase to 70 °C for a certain holding time, before being returned to 25 °C. The foregoing description represents one complete cycle.

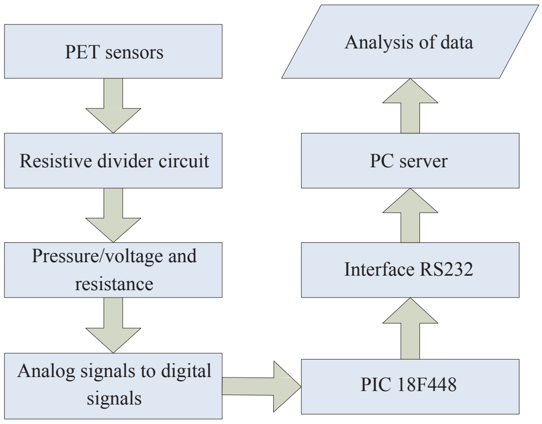


Fig. 5. (Color online) Flow chart showing process of experiment.

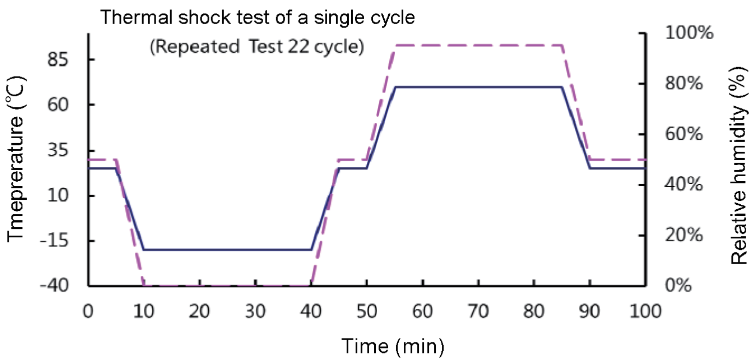


Fig. 6. (Color online) Thermal shock curve of sensor pad.

The fixed load and contact area borne by the sensor pad resulted in a maximum load of 25 kg/300 cm^2. Over thirty thousand measurements were recorded. We also observed the reaction resistance value and stability of the sensor pad. All experiments were conducted five times, the results of which are expressed as the mean continuous changes in resistance over a prolonged period as an indication of the stability of the sensor pad.

4.2 Relationship between surface state and thermal shock

The purpose of the final experiment was to determine whether changes in the external environment over an extended period would cause the ink layer in the sensor to undergo stripping or shedding, as evidenced by the accumulation of precipitate on the surface layer of the foamed plastics.

In this investigation, we focused on using scanning electron microscopy (SEM) and atomic force microscopy (AFM) to measure changes in the thickness of the oil ink, variations in the surface roughness, and whether stripping or shedding occurred. The samples were cut to form squares 100 × 100 mm^2, which were then embedded in phenolic plastic. AFM was used to observe the contours of the sensor films in three-dimensions. The AFM results were then used to reconstruct a three-dimensional image representing the true plane of the oil ink on the sensor films. As shown in Fig. 7, the surface of the printed oil ink was very flat. As shown in Fig. 8(b), changes in surface roughness were viewed as an indication that the PET film was undergoing stripping, which resulted in the formation of protruding tips, which could cause abnormal tip discharge.

5. Results and Discussion

After finishing the thermal shock experiment, the samples were removed from the furnace and allowed to sit for 48 h to stabilize. We then conducted pressure tests under a load of 25 kgf over a fixed area of 300 cm^2. Each sample underwent more than 30000 applications of pressure. Loading was applied at a relatively slow speed of 6.5 mm/15 s until the surface of the sensor pad was depressed, whereupon the pressure plate remained static for 30 s before being removed at a speed of 6.5 mm/15 s. The total duration of each test was 1 min. A data interception control card was used to record and store the resistance values every minute.

Figure 9 lists variations in resistance values for each module. The front half of the curve (until 15000 cycles) is flat, whereas between 15000 and 20000 cycles, the curve presents a linear relationship between the application of load and the resistance values generated in the sensor pad. This is a clear indication that free electrons pass through the silver layer below the graphite layer, as the silver layer provides a large number rapid channels for a large high-speed transmission capacity. The high-speed transmission capacity of the electric current was previously 15000 cycles, so the resistance value is very small and the reaction of the contact signal is fast.

In this study, considering the rigors of the thermal shock tests, the resistance values from all the module curves remained very stable, even before subjecting the sensor pad to 15000 cycles of repeated pressure load.

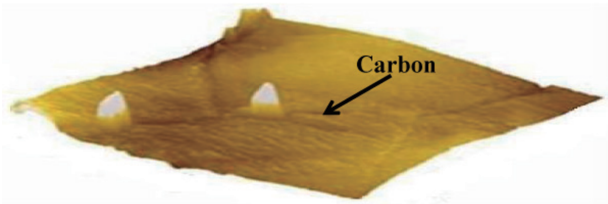
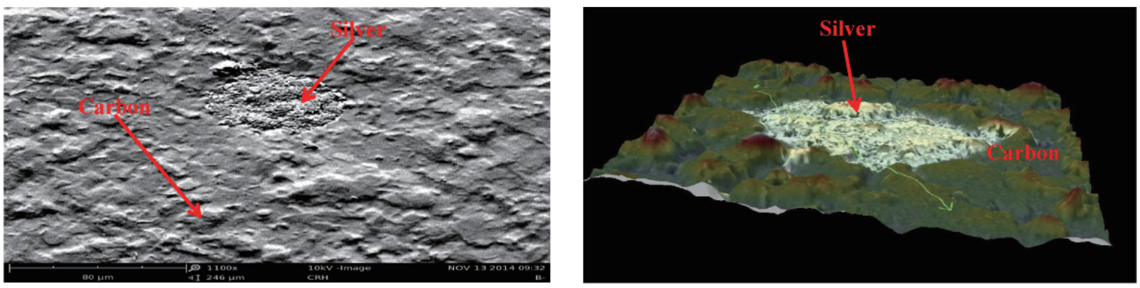


Fig. 7. (Color online) Surface of the printed oil ink, which appears very flat.



(a) (b)

Fig. 8. (Color online) (a) Plane image and (b) stereoscopic image of ink layer after undergoing repeated loading.

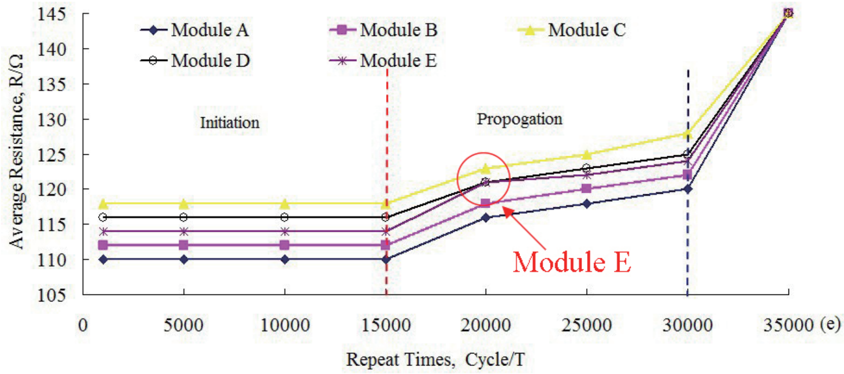


Fig. 9. (Color online) Relationship between number of repetitions of withstanding test of load and the resistance value.

The curve in module E of Fig. 9 shows variations in the resistance values of the sensor undergoing repeated load. After 20000 cycles of repeated pressure, the resistance values in module E increased rapidly from 114 to 117 Ω. Microscopic observation revealed a small amount of stripping of the ink layer from the PET film surface in the sensor pad, as shown in Fig. 8(b). This is clear indication that free electrons (electric current) passed through the silver layer, and further, that water vapor led to the formation of a black layer comprising oxidized silver, which explains the unstable resistance values obtained in module E.

This problem occurred only in module E; i.e., none of the other modules were similarly affected.

5.1 Surface state and qualitative analysis

The SEM results in Fig. 10 illustrate the thickness of the ink layer on the film in the sensor, which was measured after subjecting the device to 30000 cycles of pressure testing. The graphite layer showed clear signs of stripping, wherein the final average thickness of the ink layer was 4.1–4.8 μm. Note that these values are the average of five measurements obtained from various locations in each module of the device, as shown in Table 1. The resulting resistance values were between 110 and 145 Ω.

Even after 30000 cycles, the final thickness of the oil ink remained at >4 μm. The warning function of the sensor pad remained operable, despite the stripping off of the graphite layer from the oil ink. It appears that the toughness of the silver paste added to the flexibility and stress resistance of the sensor pad.

The service life of the sensor pad is 6–8 months, which is a considerable improvement over existing devices with an expected lifespan of just 3 months. These findings demonstrate that the proposed manufacturing process and design of the device extended the service life and reliability of the product two-fold.

Figure 7 presents an SEM image showing the three-dimensional plane of the oil ink on the sensor after 30000 cycles of pressure testing. It should be noted that the surface remained flat, with no protrusion along the edges, thereby eliminating the problem of discharge from the tips, which could otherwise skew the results, as shown in Fig. 8(b).

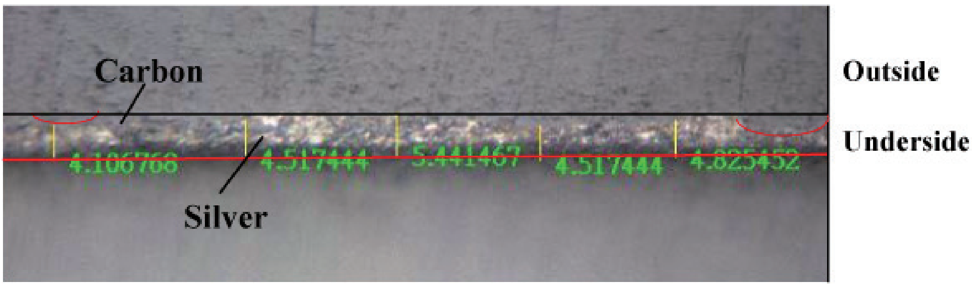


Fig. 10. (Color online) Thickness of the ink layer after repeated loads.

Table 1
Relationship between repeated times and ink film thickness.

Module	Thickness (μm)			
	15000 cycles	20000 cycles	30000 cycles	Average
A	5.8	5.5	4.8	5.4
B	5.5	5.2	4.5	5.1
C	5.3	4.5	4.3	4.7
D	5.4	4.3	4.1	4.6
E	5.6	4.3	4.1	4.8
Average	5.5	4.8	4.4	4.9

6. Conclusions

In this study, we developed a novel sensor pad with a sandwich structure. We then sought to determine the relationship between an external positive load applied to the device and the resulting resistance values to obtain an indication of changes in the surface layer of the ink layer.

Commercially available sensor pads have a lifespan of only three to six months (used an average of 20 times per day/six months: 3600 times). The proposed manufacturing method and modified graphite structure can extend the service life of sensor pads to six or even eight months (i.e., 15000 applications of force).

Our findings provide a valuable reference for the structural design and manufacturing of sensor pads. Experimental results confirm that the resistance of the sensor pad is directly proportional to the size of the repeated load. Minor stripping and shedding began to appear between the 2000th and 3000th cycles; however, this did not affect the conduction function of the device.

Our experimental results validate the reliability and stability of the sensor pad; i.e., that resistance values stabilize rapidly following the application or release of pressure. No problems were observed with regard to foamed plastic (no elastic fatigue) in the material of the sensor pad, which could otherwise lead to structural failure in which the contact point would be unable to rebound.

Future studies will involve pre-clinical patients getting into or out of bed and sleep sensing tests to verify the effectiveness of the sensor pads. We will also seek to integrate these sensor pads in bedspreads, floor mats, possibly employing photoelectric sensors in other products. The proposed sensor pad will also be combined with an events interpretation algorithm as well as information and communications technology to establish a more comprehensive, and yet unobtrusive, system for the monitoring of patients with sleep disorders and the elderly to facilitate home health management and care services.

Acknowledgements

We would like to thank Solid Year Co., Ltd. and ITRI for their assistance in this study.

References

1 D. De Rossi, F. Carpi, F. Lorussi, A. Mazzoldi, E. P. Scilingo, and A. Tognetti: Sens. Proc. IEEE **2** (2002) 1608.

2 M. Pacelli, G. Loriga, N. Taccini, and R. Paradiso: Proc. 3rd IEEE EMBS Int. Summer School Symp. Med. Devices Biosens. (Boston, MA, 2006).

3 S. Lokavee, N. Watthanawisuth, J. P. Mensing, and T. Kerdcharoen: Proc. Biomed. Eng. Int. Conf. (BMEiCON) (Chiangmai, Thailand, 29–31 January, 2012) pp. 71–75.

4 The Wikimedia Foundation Institution: Homepage of The Wikimedia Foundation Institution, http://en.wikipedia.org/wiki/Sandwich-structured_composite (accessed March 2015).

5 The Wikimedia Foundation Institution: Homepage of The Wikimedia Foundation Institution, http://en.wikipedia.org/wiki/Thixotropy (accessed March 2015).