A Wireless Pressure Measurement System Based on TiO_2 Interdigitated Sensors

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Abstract—**The ability to monitor pressure remotely is of particular importance in medical and environmental applications as it is less labour intensive, safer and offers peace of mind to the general public. To meet this demand, a prototype system using TiO_2 thick film interdigitated capacitors has been developed. The circuit is based on the principle of capacitance-frequency-voltage conversion and has been designed to minimize power consumption. The sensor was tested under hydrostatic pressure ranging from 0 – 17 kPa and high sensitivity (ΔV=47 mV) with low hysteresis (4 %) was recorded. It can be seen that this approach may provide cost effective, reliable devices for wireless sensing applications.**

I. INTRODUCTION

CCTV cameras have become an everyday occurrence on our streets, monitoring the movement of people and recording crime or other suspicious events. In the future, continuous wireless monitoring of biological and environmental situations will also become commonplace, working to protect our health and safety. Aging populations, and increased stress levels due to the modern pace of life mean that many hospitals and GP's offices are under increasing pressure [1]. The ability to monitor patients in their homes may result in a higher quality of life for patients, while knowledge of environmental situations such as water levels and quality can give researchers important information and offer peace of mind to the general public [2].

Of the various physical parameters, which can be measured, pressure is of particular importance in medical, environmental and industrial applications. The ability to place a sensor in the desired location and monitor these changes remotely has many advantages. In the automotive industry, measurement of temperature and pressure in car and truck tyres may be used to help prevent serious accidents caused by punctures [3]. In medical research, physiological pressure measurement can be a useful aid to increase understanding in areas such as cardiology, gastroenterology, urology, neurology and rehabilitation [4].

Some of the major requirements for remote pressure sensing include low power consumption, correct sensor size and shape, reliability and low cost [5]. These parameters are especially stringent when the system is to be used in biomedical pressure monitoring where space is at a premium and power is not easily available. Capacitive sensors are particularly capable of meeting these demands [6]. Of the various fabrication methods available, thick film devices offer a reliable and cost effective approach to sensor fabrication, as medium scale production can meet current market demands for medical sensors [7].

In this work, a prototype system, based on capacitance-frequency-voltage conversion, has been developed. This system wirelessly transmits changes in capacitance with pressure to a receiver, which can operate at a range of 75 m in buildings and 300 m on open ground. The sensor is a capacitor with interdigitated electrodes. The dielectric layer was prepared using titanium oxide (TiO_2). Titanium dioxide is commonly used in biomedical and industrial applications, as it is considered chemically benign [8]. Furthermore, it is not significantly affected by humidity, making it suitable for environmental monitoring [9]. There are three main phases: rutile, anatase and brooktite. At room temperature rutile is thermodynamically stable, while anatase exists in a metastable state [10, 11]. Normal intra cranial pressure is approximately 1 kPa, while pressure in the gastrointestinal tract range for 6 – 16 kPa and arterial blood pressure ranges from 13 – 18 kPa. As a result, it was decided to test the device under hydrostatic pressure ranging from 0 – 17 kPa.

II. EXPERIMENTAL

The capacitors used in this study were fabricated by screen-printing on Melinex® substrates. The electrodes were formed using DuPont 4929 silver conductive paste and each had 25 fingers of length 6 mm and separation of 0.2 mm.

To form the dielectric layer, TiO_2 powder (supplied by Riedel-De Haen Ag Seelze-Hannover) was mixed with isopropanol to form a slurry, which was wet ball milled in

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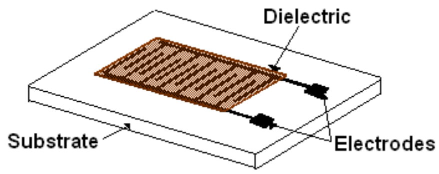

Figure 1. Structure of a thick film interdigitated capacitor

alcohol for 24 hours. The mixture was dried at 120 ^{o}C to evaporate the alcohol. The powder was then placed under 2 tons of pressure to form a pellet, which was fired at 1250˚C (rate of 5˚C per minute) in a vacuum of 6 x 10^{-3} mbar for five hours, followed by cooling (rate of 3˚C per minute).

After firing, the solid pellet was ground down to a powder using a Gy-RO Mill for 10 minutes. Scanning electron microscopy (SEM) was used to examine the powders particle size, before and after firing. The powders were mixed with 7 wt.% of polyvinyl butyral (PVB), which was used as the binder. Ethylenglycolmonobutylether was the solvent used to form the paste. Once prepared, 3 layers of TiO_2 paste were screen-printed over the Ag interdigitated electrodes to form the capacitors. The baseline capacitance recorded for each device is approximately 7 pF. Fig. 1 shows the basic structure of an interdigitated capacitor.

The device was tested under hydrostatic pressure by connecting it to specially designed interface, transmitter and receiver circuit. A thin, flexible, waterproof membrane was used to protect the sensor from the liquid environment while the circuit was placed in weatherproof housing. During testing, the change in capacitance for pressures ranging from 0 – 17 kPa was converted to a frequency change and wirelessly transmitted to an external receiver. The receiver then converts this frequency to a voltage, which is displayed as the output.

III. RESULTS AND DISCUSSION

A. *Scanning Electron Microscopy*

Heating anatase TiO_2 to temperatures in excess of 800 – 1000 ^{o}C results in an irreversible phase transition to rutile TiO_2 [9, 11, 12]. This is the result of some of the anatase parallel octahedra rotating by 90^{o} and is accompanied by considerable grain growth and a more dense and coarse nanostructure [13].

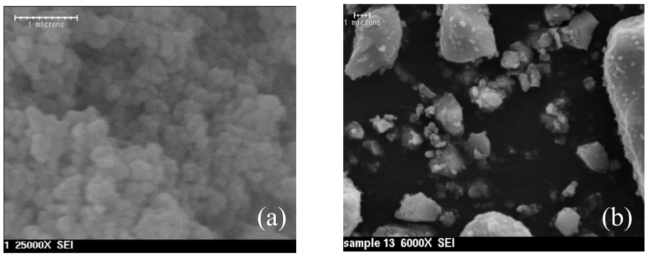

Figure 2. SEM of TiO_2 powder (a) prior to firing (b) after firing

SEM was used to determine the powders particle size, as it can have a large bearing on the characteristics of the film. It has been reported that nanocrystallite TiO_2 exhibits plastic rather than brittle behaviour, with the degree of ductility increasing in response to decreasing grain sizes [14].

It can be seen from fig. 2 (a) that the particle size prior to firing is less than 0.5 μm. Firing the pellet at 1250˚C has caused coalescence of the TiO_2 powder, increasing the particle size, as shown in fig. 2 (b). As a result, careful milling of the powder after firing is essential to achieve uniform particle sizes.

B. *Interface, transmitter and reciever circuit*

To test the response of the developed thick film pressure sensor an efficient wireless interface, transmitter and receiver circuit was developed. A block diagram of the system is shown in fig. 3.

The most important feature of the sensor interface circuit is an integrated capacitance to frequency converter. This connects the sensor to the telemetry subsystem. The output frequency can be known from (1),

$$f_{out} = \frac{1}{C_x (R_2 + 2R_1) \ln 2} \qquad (1)$$

where, f_{out} is the output frequency, C_x is the sensor capacitance and the resistors R_1 and R_2 are used to setup the timer frequency. In this case they have the value R_1 = 100 kΩ and R_2 = 2 MΩ.

The Frequency Shift-Keying (FSK) transmitter of 160Kbps has been selected to send the signal coming from the CMOS oscillator. The main advantage of using such a high-speed transmitter is that it can cope with large changes in capacitance during operation (3 to 55pF). At the receiver side, a low power Phase Locked Loop (PLL) unit is used as a frequency to voltage converter to display the output signal in terms of voltage levels.

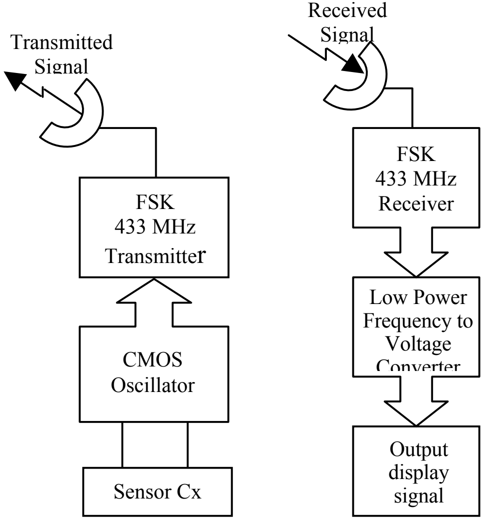

Figure 3. Block diagram of the interface, transmitter and receiver circuits

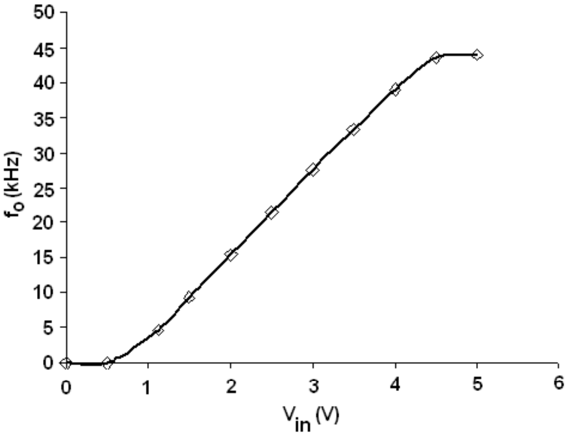

Figure 4. Frequency/Voltage characteristics of the voltage controlled oscillator

The relationship between frequency, *f*, and voltage, *V*, can be seen in (2),

$$f = V \times 13.1 kHz \tag{2}$$

where the value of 13.1 kHz/V is the slope of the graph showing the change in frequency with voltage for the voltage controlled oscillator in fig. 4.

C. *Sensitivity of theTiO$_2$ interdigitated capacitor*

Using the system outlined in section III B, each sensor was tested under hydrostatic pressure by increasing the sensors depth in a liquid environment. As the pressure is increased, the sensors capacitance also increases due to deformation of the dielectric layer. This change is displayed as a corresponding voltage change at the receiver end of the circuit, as described by (1) and (2).

For sandwich capacitors under pressure, the change in capacitance can be known by examining changes in the distance between the plates (or electrodes) in addition to the dielectric properties of the film between them. The situation for interdigitated capacitors is more complex, with the capacitance being largely dependant on the number of fingers (*N*), their length (*L*) and width (*W*), in addition to the gap between electrodes (*G*), spatial wavelength ($\lambda = 2(W+G)$) and the metallization ratio ($\eta = 2W/\lambda$) [15]. Any changes in capacitance are due to deformation of the dielectric layer, deposited over the electrodes and the overall capacitance of a device is generally determined using a conformal mapping technique [15]. Previous investigations into the sensitivity of an interdigiated capacitor with a dielectric layer of PVDF showed the device had a high sensitivity to hydrostatic pressure with low hysteresis [16].

The sensitivity of each device was taken to be the maximum change in voltage over the entire pressure range. For the sensors tested as part of this work, it was found to be 47 mV, which corresponds to a pressure of 17 kPa, as shown in fig. 5. It can be seen that the sensors response attenuates as the pressure increases. This can be partially attributed to the non-linear characteristics of the PLL on the receiver side of the circuit. The high sensitivity recorded may be caused by the small particle size of the TiO$_2$ powder and the combination of TiO$_2$ powder with PVB binder (an elastomer), as mixing a brittle ceramic with an elastic second phase has been shown to reduce its yield strength, making it more easily deformed under pressure [14].

Hysteresis was measured to be the maximum difference between loading and unloading cycles as percentage of full-scale deviation. In this case the hysteresis was calculated to be 4 %, which corresponds to a voltage difference of 2 mV. The result is shown in fig. 6. This result corresponds well with values of hysteresis recorded for polymer devices using a capacitor configuration (5 – 30 %) [16].

Finally, the materials repeatability was measured by constant loading and unloading. The result over 5 cycles is shown in fig. 7. The maximum difference between these was measured to be 4 mV, which is 8 % when expressed as a percentage of full scale.

Previous investigations into the use of TiO$_2$ interdigitated capacitors with three fingers for use as strain gauges have shown that the material has a gauge factor of 5 with hysteresis of 0.7 % and repeatability of 1.22 % [17]. Changes in the values of hysteresis and repeatability of the device can be explained by considering the larger size of the device in addition to the change in substrate, which can affect the reliability of the device [18].

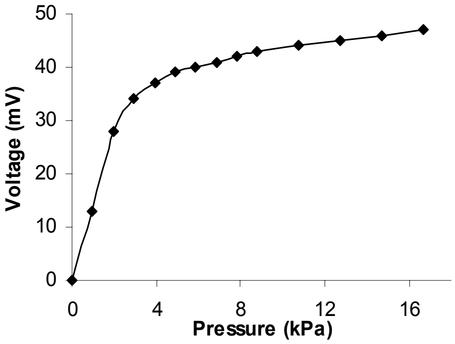

Figure 5. Change in output voltage with pressure in the range 0 – 17 kPa

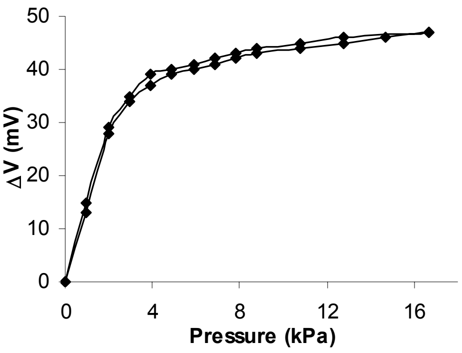

Figure 6. Hysteresis measured for TiO$_2$ sensors in the range 0-17 kPa

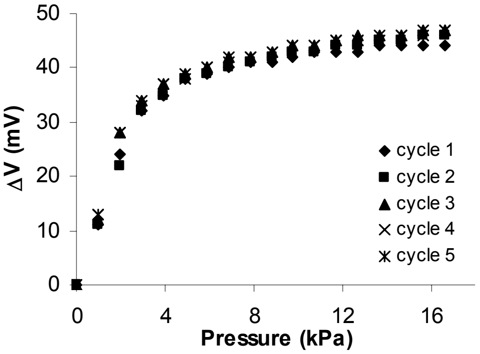

Figure 7. Repeatability of TiO$_2$ sensors in the range 0-17 kPa

IV. CONCLUSIONS

In this work a wireless pressure measurement system using a thick film capacitor with TiO$_2$ as the dielectric layer was evaluated. The system was tested under hydrostatic pressure ranging from 0 – 17 kPa. It can be seen from the results that the sensor showed good sensitivity to changes in pressure and the prototype circuit was successful in transmitting changes to the receiver. These results can be used to form the basis of a wireless monitoring system.

ACKNOWLEDGMENT

This research was supported by the Enterprise Ireland Commercialization Fund 2003, as part of the MIAPS project, reference no. CFTD/03/425. Funding was also received from the Irish Research Council for Science, Engineering and Technology: funded by the National Development Plan.

REFERENCES

[1] C. May, T. Finch, F. Mair, and M. Mort, "Towards a wireless patient: Chronic illness, scarce care and technological innovation in the United Kingdom," *Social Science & Medicine*, vol. 61, pp. 1485-1494, 2005.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, pp. 393 - 422, 2002.

[3] G. Schimetta, F. Dollinger, G. Scholl, and R. Weigel, "Optimized Design and Fabrication of a Wireless Pressure and Temperature Sensor Unit Based on SAW Transponder Technology," presented at Microwave Symposium Digest IEEE MTT-S International, Denver, USA, 2001.

[4] C. Yang, C. Zhao, L. Wold, and K. R. Kaufman, "Biocompatibility of a physiological pressure sensor," *Biosensors and Bioelectronics*, vol. 19, pp. 51-58, 2003.

[5] T. Grandke and W. H. Ko, *Sensors: a comprehensive survey*, vol. 1. Weinheim and New York: VCH Verlagsgesellschaft mbH and VCH Publishers Inc., 1989.

[6] R. Puers, "Capacitive sensors: when and how to use them," *Sensors and Actuators A*, vol. 37-38, pp. 93-105, 1993.

[7] M. R. Neuman, R. P. Buck, V. V. Cosofret, E. Linder, and C. C. Liu, "Fabricating biomedical sensors with thin-film technology," *IEEE Engineering in Medicine and Biology Magazine*, vol. 13, pp. 409 - 419, 1994.

[8] D. M. Brunette, *Titanium in medicine: material science, surface science, engineering, biological responses and medical applications*. London: Springer, 2001.

[9] E. Traversa, M. L. Di Vona, S. Licoccia, M. Sacerdoti, M. C. Carotta, L. Crema, and G. Martinelli, "Sol-Gel Processed TiO$_2$-Based Nano-Sized Powders for Use in Thick-Film Gas Sensors for Atmospheric Pollutant Monitoring," *Journal of Sol-Gel Science and Technology*, vol. 22, pp. 167-179, 2001.

[10] Z. Liu, L. Hong, and B. Guo, "Physicochemical and electrochemical characterization of anatase titanium dioxide nanoparticles," *Journal of Power Sources*, vol. 143, pp. 231-235, 2005.

[11] V. Guidi, M. C. Carotta, M. Ferroni, G. Martinelli, and M. Sacerdoti, "Effect of Dopants on Grain Coalescence and Oxygen Mobility in Nanostructured Titania Anatase and Rutile," *Journal Of Physical Chemistry B*, vol. 107, pp. 120-124, 2003.

[12] D.-J. Won, C.-H. Wang, H.-K. Jang, and D.-J. Choi, "Effects of thermally induced anatase-to-rutile phase transition in MOCVD-grown TiO$_2$ films on structural and optical properties," *Applied Physics A Materials Science & Processing*, vol. 73, pp. 595-600, 2001.

[13] M. Sacerdoti, M. C. Dalconi, M. C. Carotta, B. Cavicchi, M. Ferroni, S. Colonna, and M. L. D. M. L. D. Vona, "XAS investigation of tantalum and niobium in nanostructured TiO$_2$ anatase," *Journal of Solid State Chemistry*, vol. 177, pp. 1781-1788, 2004.

[14] B. Jiang and G. J. Weng, "A theory of compressive yield strength of nano-grained ceramics," *International Journal of Plasticity*, vol. 20, pp. 2007-2026, 2004.

[15] R. Igreja and C. J. Dias, "Analytical evaluation of the interdigital electrodes capacitance for a multi-layered structure," *Sensors and Actuators A*, vol. 112, pp. 291 - 301, 2004.

[16] A. Arshak, K. I. Arshak, D. Morris, O. Korostynska, and E. Jafer, "Development Of PVDF Thick Film Interdigitated Capacitors For Pressure Measurement On Flexible Melinex Substrates," presented at MRS Spring Meeting, San Francisco, 2005.

[17] A. Arshak, K. Arshak, D. Morris, O. Korostynska, and E. Jafer, "Investigation of TiO2 thick film capacitors for use as strain gauge sensors," *Sensors and Actuators A: Physical*, vol. 122, pp. 242-249, 2005.

[18] C. A. Harper, *Handbook of thick film hybrid microelectronics: a practical sourcebook for designers, fabricators and users*. New York: McGraw-Hill Book Company, 1974.