Investigation into the pressure sensing properties of PVDF and PVB thick film capacitors

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***Abstract**: This paper examines the sensitivity of polyvinylidene fluoride (PVDF) and polyvinyl butyral (PVB) capacitors to pressures ranging from 0 – 100 kPa. The capacitors were formed by screen-printing onto flexible substrates and have an active area of 2 x 3 mm^2. There are no moving parts and as a result the complexity of sensor design, fabrication and packaging issues may be reduced. After fabrication, sensors were adhered to planar and cylindrical surfaces and interfaced with an AD7746 24-bit capacitance to digital converter. This allowed precise measurements to be taken. It has high linearity and accuracy and can accept up to 17 pF absolute capacitance. The pressure was applied by housing the sensor in an airtight container and pumping air into the system to increase the pressure. It was found that PVDF devices on planar surfaces exhibited the largest response to the application of pressure. This was further increased for devices placed on cylindrical surfaces. It is thought that this is due to cracking of the thick film upon bending of the substrate. The results suggest that PVDF and PVB are suitable candidate materials for use in a pressure monitoring system.*

1. Introduction

Pressure measurement is an essential tool for a wide range of industrial and medical applications. For example, pressure measurement is vital in developing understanding of the aerodynamic behaviour of planes and ground vehicles [1]. In biomedical applications, sensors are commonly attached to medical equipment such as endoscopes, to provide doctors with information regarding how much pressure they are exerting on internal organs and tissue [2].

Wireless sensor systems are increasingly popular for monitoring biological, environmental and industrial conditions. The absence of wires alleviates discomfort for patients. In addition, allowing measurements to be taken from a distance can protect the safety of industrial workers. As a result, much research has been undertaken, particular in the development of miniaturized wireless systems for pressure measurement. These can be used for the monitoring of intracranial and intraocular pressure, along with the pressure inside many body cavities such as the gastrointestinal and urinary tract [3, 4]. This information can be used for clinical studies in areas such as cardiology and pulmonology [5].

Such systems must be small in size, reliable, rugged and cost effective [6]. Due to the size requirements, MEMS sensors are often chosen for wireless pressure monitoring applications. However, the presence of moving parts complicates fabrication and packaging, which is particularly important when the sensor is to be placed inside the body [7]. Furthermore, the process is only cost effective if sensors are produced in high volumes (in excess of 10^5-10^6 devices per year) [8].

An alternative approach is to use devices fabricated by thick film technology. With this method, layers of conductive and dielectric paste can be deposited onto glass, alumina or polymer substrates. The most significant advantages to this approach are the rugged nature of the thick films and the flexibility that the process allows in terms of the choice of material. A wide range of oxides and polymers can be combined to produce devices with the required physical and chemical properties [9]. Finally, the devices can be fabricated without any moving parts removing some of the complex issues associated with MEMS sensors.

In this paper, the pressure sensing properties of two thick film capacitors, based on a polyvinylidene fluoride (PVDF) or polyvinyl butyral (PVB) dielectric were investigated. A capacitor configuration was used as it has been reported to provide higher sensitivity with lower power consumption, which is important for wireless sensing applications.

PVDF is a low-density semi-crystalline material, consisting of long repeated chains of $–CF_2$-CH_2- molecules. It is popular for acoustic, ultrasonic and pressure related applications as it can be formed into sheets, which are flexible, allowing for their use in situations where complex geometries are required [10].

The crystalline region of the polymer can be made up of a number of polymorphs. Of the various types, the α- and β-phase are most commonly used. The β-phase is piezoelectric and is commonly used in the development of plantar pressure sensors, for the measurement of explosive force and the investigation of shock events though the use of strain gauges [11-13].

When piezoelectric PVDF is used in a capacitor, charge will be developed across the plates in response to applied pressure. However, if this load does not vary, the charge will decay with time [14]. If this is the case, α-phase PVDF may be more useful. For example, it has successfully been employed in the fabrication of thick film strain gauges working on a capacitive principle [15]. Furthermore, interdigitated electrodes, covered with a PVDF dielectric layer have been incorporated into a wireless measurement system and showed good sensitivity to hydrostatic pressure [16].

PVB is an elastomer, which is commonly used as a binder for thick film pastes [16]. More recently, it has been prepared in solution, with conductive fillers; to produce a drop coated composite film for pressure sensing applications [17]. In this investigation, it was found that the device displayed good sensitivity and repeatability and has potential for use in thick film capacitive sensors.

2. EXPERIMENTAL PROCEDURE

In this work, thick film PVDF and PVB capacitors were formed by screen-printing onto flexible Melinex® substrates using a DEK RS 2102 automatic screen-printer. For PVDF, the paste was prepared by combining it with 7 wt.% of binder (ethyl cellulose) and a suitable amount of solvent (terpinol-α). PVB acts as the functional material and the binder. It was combined with ethyleneglycolmonobutylether to form a paste. The sensor structure is shown in Fig. 1. The conductive layers were formed using Ag paste. After fabrication, devices were adhered to planar and cylindrical surfaces.

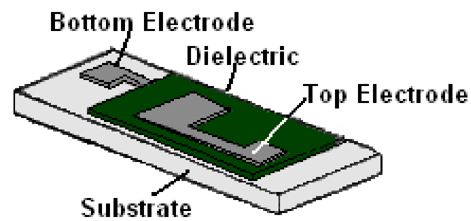

Fig.1. Layout of PVDF and PVB Sandwich Capacitors.

The electrical properties of the sensors on planar surfaces were then investigated in the range 100 Hz to 13 MHz, using an HP 4192A LF Impedance Analyser. This illustrates the frequency dependence of the device, which may be important for the interface circuitry.

Pressure sensors find applications in a wide range of environments and in some situations the temperature cannot easily be controlled. Therefore, an accurate knowledge of the effect of temperature on each device can be useful for temperature compensation techniques.

To investigate the effect of temperature on devices a test rig based on the Peltier effect was employed. The temperature was varied between 10 and 60 °C in steps of 5 °C using a controlled isothermal substrate holder. This is driven from customised electronics hardware, which is connected to a National Instruments Data Acquisition (DAQ) card. Software, written in LabWindows/CVI was used to control the DAQ and measure the change in resistance.

The change in sensor capacitance with pressure was investigated by integrating the sensors with an AD7746 24-bit capacitance to digital converter. The sensor and interface circuit was sealed in an airtight container. The pressure was then varied in the range 0 – 100 kPa.

3. RESULTS AND DISCUSSION

3.1. Interface Circuit

As high precision capacitive measurements are required for this application an AD7746 24-bit capacitance to digital converter was employed [18]. This chip combines 19-bit resolution at a 16.6 Hz data rate with high accuracy. The input range is between ± 4 pF. However it can accept up to 17 pF absolute capacitance through compensation by the on-chip digital to capacitance converter (CAPDAC). A block diagram of the AD7746 is shown in Fig. 2.

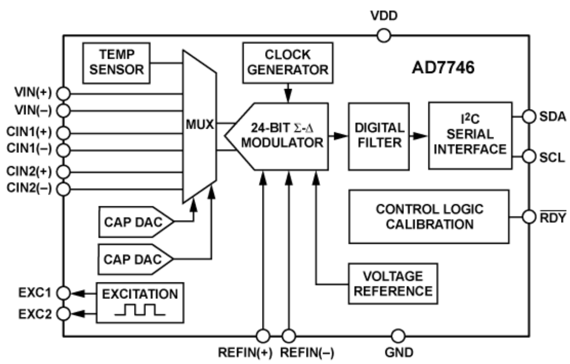

Fig. 2. Schematic diagram of the AD7746 capacitance to digital converter

The ADuC831 microprocessor was used to control the AD7746. It was interfaced with the capacitance to digital converter using the I^2C bus connections on the MCU. The ADuC831 has a built in I^2C and RS232 bus controller simplifying programming.

Another advantage of this system is the potential to make the system wireless. This can be achieved by creating an invisible serial link between the ADuC831 and a receiver base station using a pair of SPM2 modules. The SPM2 module is connected to the TX/RX data lines of the ADuC831 serial port. The module packetizes data received on the RX line and transmits it wirelessly to a receiving SPM2 module where it is decoded and relayed to a PC, through the serial port, allowing the collection, storage and analysis of the measurements. The SPM2 modules operate at low power and have several configurable parameters such as baud rate, throughput, addressing and remote wakeup. Advantages also include a built in terminal interface for test and configuration.

3.2. AC Properties of PVDF and PVB Sensors

Fig. 3 shows the frequency dependence of the PVDF and PVB thick film sandwich capacitors. It can be seen that PVB is extremely stable over the entire range. On the other hand, the capacitance of PVDF devices can be seen to decrease with frequency, particularly in the range 100 – 1000 Hz. As a result, it can be concluded that the optimum frequency range for these devices is above 1 kHz.

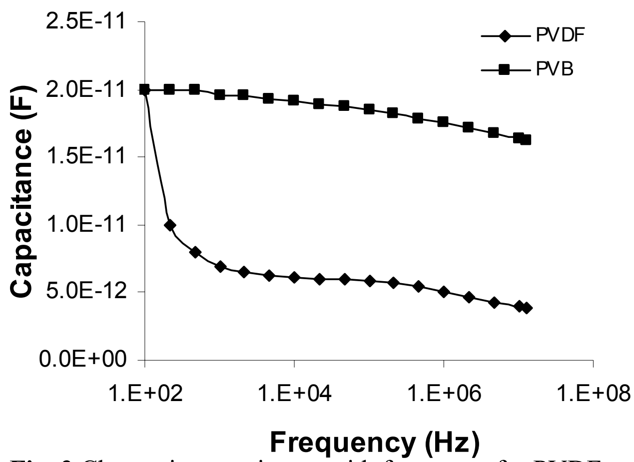

Fig. 3 Change in capacitance with frequency for PVDF and PVB capacitors

3.3. Temperature Effects

There have been some concerns about the temperature dependence of thick film devices, particularly when they are fabricated so that the capacitance is measured through deformation of a flexible membrane [19]. Although this is not the case in this work, the change in capacitance with temperature was measured for each sensor between 10 ^{o}C and 60 ^{o}C. Fig. 4 illustrates the results for PVDF and PVB.

It can be seen that at low temperatures, the capacitance of the PVDF sensor rises considerably. Similar behaviour has been recorded, particularly for a PVAc/carbon black sensor, where the resistance was observed to increase sharply on cooling. It is thought that when the temperature is brought to below room temperature, moisture in the air will condense on the sensor surface, leading to a sharp increase in capacitance. This effect can be reduced by coating the device [17].

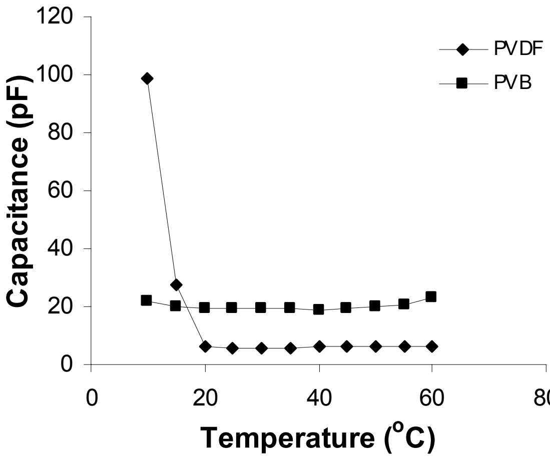

Fig. 4 Change in capacitance with temperature for PVDF and PVB devices

The temperature coefficient of capacitance (TCC) is a measure of the parts per million change in capacitance per degree change in temperature. It can be calculated from (1)

$$TCC = \frac{C_{T_2} - C_{T_1}}{C_{T_1} \Delta T} 10^6 \qquad (1)$$

where, C_{T1} is the capacitance at temperature 1, C_{T2} is the capacitance at temperature 2 and ΔT is the change in temperature. It has been shown that the TCC is highly dependent on the permittivity of the material and therefore will depend on the type of polymer [20].

The TCC was calculated for PVDF and PVB in two temperature ranges, 10 ^oC – 20 ^oC and 20 ^oC – 60 ^oC. The results are shown in Table 1. Generally speaking, the TCC for a thick film capacitor is expected to lie in the region of 1500 – 3000 ppm/^oC. It can be seen that the TCC calculated for region 1 is considerably higher than this for both materials.

Polymer	**TCC Region 1**	**TCC Region 2**
PVDF	93827 ppm/^oC	1316 ppm/^oC
PVB	12325 ppm/^oC	9346 ppm/^oC

Tab. 1. TCC in region 1 and region 2 for PVDF and PVB

For region 2 it is found that the TCC for PVDF is better than what is typically expected. However, this is not the case for PVB devices. This can be attributed to an increase in capacitance, which occurs when the temperature reaches 40 ^oC. When the region between 20 ^oC and 40 ^oC is examined a TCC of 927 ppm/^oC is calculated. Therefore the capacitor is most suited to use in this range, making it useful for biomedical or room temperature monitoring applications.

4.4. Sensitivity to Pressure

Each device was subjected to pressure ranging from 0 – 100 kPa and its maximum response recorded. The results for PVDF and PVB sensors on planar surfaces are shown in Fig. 5.

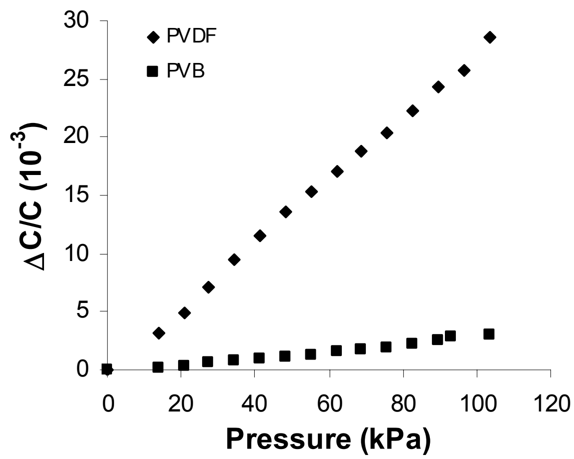

Fig. 5. Response of PVDF and PVB sensors on planar surfaces to pressure

It should be noted that, as the capacitance of the PVB sensors exceeded the maximum value allowable by the interface circuitry, it was placed in series with a 1.5 pF capacitor. The response to a maximum pressure of approximately 100 kPa was taken to be the change in capacitance, C, relative to the initial capacitance, C_o. It was recorded to be 28.5 and 3.04 [$\Delta C/C_o$ (10^{-3})] for PVDF and PVB respectively.

Each sample was tested a number of times and the hysteresis was determined by measuring the difference between two consecutive cycles and expressing it as a fraction of the full-scale deviation. Some hysteresis is expected for polymer devices and is attributed to slippage of the polymer chains.

The hysteresis for a PVDF and PVB sample on a planar surface has been measured to be 2 % and 4 % respectively. The results are shown in Fig. 6. Typical values of hysteresis for polymer thick film devices lie in the region of 6 % to 30 % [21].

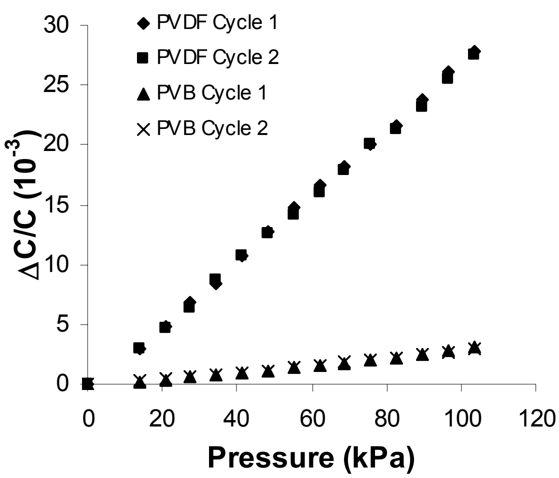

Fig. 6. Hysteresis for PVDF and PVB devices on planar surfaces

PVDF and PVB sensors on cylindrical surfaces were then exposed to pressure. The results are shown in Fig. 7. It can be seen that the response of both sensors has been improved, being 44.19 and 23.58 [$\Delta C/C_o$ (10^{-3})] for PVDF and PVB respectively.

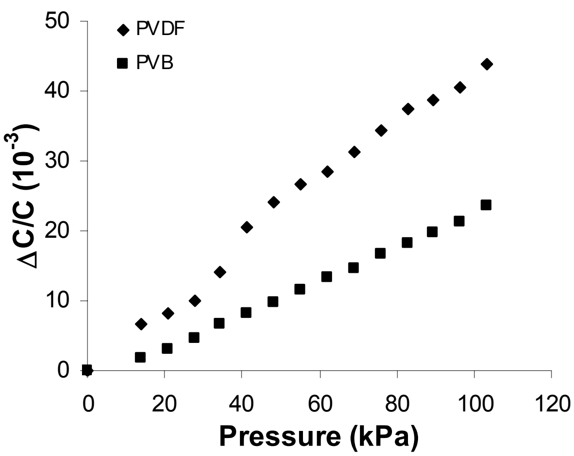

Fig. 7. Response of PVDF and PVB sensors on cylindrical surfaces to pressure

Previous investigations into the pressure sensing properties of interdigitated PVDF sensors also showed that devices exhibit an increase in sensitivity when placed on cylindrical surfaces. This increase is also accompanied by degradation in hystersis. Such behaviour is also illustrated by the sandwich capacitors used in this work. The hysteresis between two consecutive cycles for PVDF and PVB is shown in Fig. 8 and has been calculated to be 7 % and 3 % respectively.

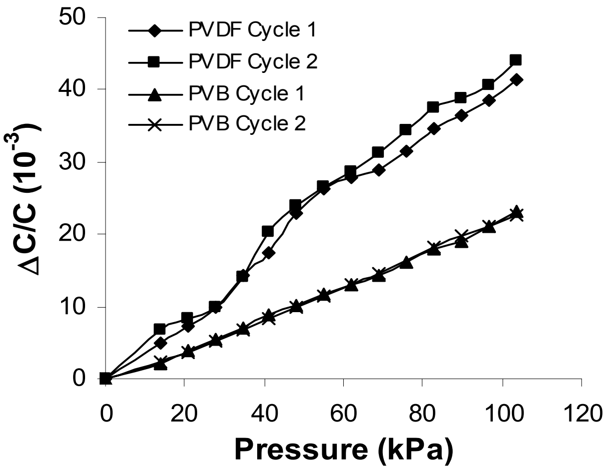

Fig. 8. Hysteresis for PVDF and PVB devices on cylindrical surfaces

The increase in hysteresis may be attributed to the presence of cracks in the polymer layer. These are increased during bending of the substrate and can lead to more instability in the film. Changes in the drying cycle can be used to promote better reflow of the polymer film, thus reducing the level of defects [16].

5. CONCLUSIONS

In this work, the pressure sensing properties of PVDF and PVB were investigated using a specially adapted interface circuit, which has the ability to be modified further in order to allow for wireless communication. Each sensor was evaluated on planar and cylindrical surfaces. It can be seen that PVDF is most suited for use in this system as the baseline capacitance is compatible with the range accepted by the circuit. In addition, the sensors show a high response to applied pressure, which is increased when they are placed on cylindrical surfaces. It can be concluded that thick film sandwich capacitors based on PVDF and PVB are suitable candidates for use in wireless pressure sensing systems.

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REFERENCES

[1] M. Zagnoni, A. Golfarelli, S. Callegari, A. Talamelli, V. Bonora, E. Sangiorgi and M. Tartagni, "A non-invasive capacitive sensor strip for aerodynamic pressure measurement," *Sensors and Actuators A: Physical*, vol. 123-124, 2005, pp. 240-248.

[2] J. Dargahi, M. Parameswaran and S. Payandeh, "A Micromachined Piezoelectric Tactile Sensor for use in Endoscopic Graspers," presented at Intl. Conference on Intelligent Robots and Systems, Victoria, B.C., Canada, 1998.

[3] U. Schnakenberg, P. Walter, G. vom Bogel, C. Kruger, H. C. Ludtke-Handjery, H. A. Richter, W. Specht, P. Ruokonen and W. Mokwa, "Initial investigations on systems for measuring intraocular pressure," *Sensors and Actuators A: Physical*, vol. 85, 2000, pp. 287-291.

[4] T. Eggers, C. Marschner, U. Marschner, B. Clasbrummel, R. Laur and J. Binder, "Advanced Hybrid Integrated Low-Power Telemetric Pressure Monitoring System For Biomedical Applications," presented at MEMS2000, Miyazaki, Japan, 2000.

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

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

[7] A. Arshak, K. Arshak, D. Waldron, D. Morris, O. Korostynska, E. Jafer and G. Lyons, "Review of the potential of a wireless MEMS and TFT microsystem for the measurement of pressure in the GI tract," *Medical Engineering & Physics*, vol. 27, 2005, pp. 347.

[8] 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, 1994, pp. 409 - 419.

[9] K. I. Arshak, D. Morris, O. Korostynska, E. Jafer, A. Arshak, J. Harris, S. Clifford and G. Lyons, "Novel silicone-based capacitive pressure sensors with high senstivity for biomedical applications," *e-polymers*, vol. 61, 2004, pp. 1-11.

[10] P. A. Payne and Q. X. Chen, "Polymer Materials for Pressure Measurement," *Physiological Pressure Measurement, IEE Colloquium on*, 1990, pp. 7/1 - 7/3.

[11] S. Urry, "Plantar pressure-measurement sensors," *Measurement Science and Technology*, vol. 10, 1999, pp. R16 - R32.

[12] P. A. Payne, Q. X. Chen, F. Moss, R. E. Banks and S. Smith, "Piezoelectric polymers and copolymers and their applications," *Molecular Electronics, IEE Colloquium on*, 1990, pp. 6/1 - 6/6.

[13] J. Knapp, E. Altmann, J. Niemann and K.-D. Werner, "Measurement of shock events by means of strain guages and accelerometers," *Measurement*, vol. 24, 1998, pp. 87 - 96.

[14] N. D. Duffy, B. Praesetyo, G. Blanchflower, R. McHugh and J. T. Herd, "PVDF touch sensors and time-of-flight force sensors for robot gripper applications," *Robot Sensors, IEE Colloquium on*, 1991, pp. 6/1 - 6/4.

[15] K. I. Arshak, D. McDonagh and M. A. Durcan, "Development of new capacitive strain sensors based on thick film polymer and cermet technologies," *Sensors and Actuators A*, vol. 79, 2000, pp. 102 - 114.

[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] K. Arshak, D. Morris, A. Arshak, O. Korostynska and E. Moore, "PVB, PVAc and PS pressure sensors with interdigitated electrodes," *Sensors and Actuators A: Physical*, vol. In Press, Corrected Proof.

[18] K. Arshak, D. Morris, K. Kaneswaran, O. Korostynska and A. Arshak, "Portable Real-Time Gamma Radiation Dosimetry System Using MgO and CeO2 Thick Film Capacitors," presented at International Conference on Sensing Technology, Palmerston North, New Zealand, 2005.

[19] A. Arshak, K. Arshak, D. Morris, O. Korostynska and E. Jafer, "Investigation of TiO_2 thick film capacitors for use as strain gauge sensors," *Sensors and Actuators A: Physical*, vol. 122, 2005, pp. 242-249.

[20] A. G. Cockbain and P. J. Harrop, "The temperature coefficient of capacitance," *Brittish Journal of Applied Physics*, vol. 1, 1968, pp. 1109-1115.

[21] K. Arshak, D. Morris, O. Korostynska and A. Arshak, "Cerium and Titanium Oxide Interdigitated Capacitors for Pressure Sensing Applications," presented at International Conference on Sensing Technology, Palmerston North, New Zealand, 2005.