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Multifunctional and miniaturized flexible sensor patch: Design and application for *in situ* monitoring of epoxy polymerization

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ABSTRACT

Sensor systems capable of *in situ*, continuous impedance measurements are expected to play an important role for a broad spectrum of applications. However, widespread use of these devices is hindered by their current form of separated sensors from bulky, expensive readout instruments. Moreover, the lack of other relevant sensing functionalities on the same system results in an incomplete understanding of the complex physical and chemical changes taking place. In this paper, a miniaturized sensor patch (MSP) with simultaneous impedance and temperature measurements and fully integrated readout is cleverly designed. By using an on-board microcontroller, sensor signal is read out locally and transmitted digitally, eliminating the noise on the signal over the transmission path. The MSP is stable over a wide temperature range (20–180 °C), and in various dielectric mediums (air, epoxies). Moreover, flexible circuit board technology based device fabrication permits further extended functionalities of the patch with off-the-shelf surface mounted devices. The MSPs were successfully applied for monitoring the polymerization processes of two epoxies, demonstrated the potential of the proposed sensor patch as an integrated and multifunctional sensing solution.

1. Introduction

Impedance sensors are devices that can measure the electrical impedance of the material to which it is attached. Since the impedance of the materials are dependent on their physical, chemical and biological properties which may change, devices that carries out continuous, *in situ* and real-time impedance measurements present an exciting opportunity for a broad spectrum of applications, such as monitoring of biological activities in human bodies [1–4], quality control of photovoltaic devices [5,6], strain, pressure and tactile sensing in wearable devices [7–11], production and structural health monitoring of polymeric composites [12,13], chemical sensing [14–16], and so on.

Despite the potential of these devices, they are still under investigation primarily as an analytic tool. At present, impedance measurements are usually carried out in idealized laboratory environment using expensive bulky instruments, combined with cumbersome calibration and cable extension techniques to the sensors [17,18]. To address this challenge, sensor systems with integrated readout circuitry were developed [19–22]. For instance, a low-power impedance-to-digital converter was built on silicon chips for sensor array microsystems towards biological applications [19]. CMOS electrochemical impedance spectroscopy biosensor arrays were designed for detecting various biological analytes [20], and prostate cancer DNAs [21]. A sensor interface integrated circuit (IC) was developed for miniaturized dielectric spectroscopy [22]. However, aforementioned systems still require external benchtop instruments, such as functional generators, clocks, amplifiers, as part of the readout circuitry. Moreover, these devices only measure the impedances of materials. Inclusion of other relevant sensing capabilities onto the same platform would enable simultaneous sensing of multiple parameters, thereof provide a complete picture of the complex biological, chemical, and physical changes taking place.

Herein, we present a flexible, miniaturized sensor patch (MSP) with sensors and integrated readout circuitry. The MSP, fabricated using flexible circuit board technology (FCB), comprises a photo-lithographically patterned interdigital sensor for impedance measurement, off-the-shelf surface mounted device (SMD) for temperature measurements, and a microcontroller unit (MCU) for data processing and communication. Taking advantage of the on-board MCU, which locally processes the data and digitally transmits it, the influence of noise on the data over a long signal path is eliminated. The MSP is capable of capacitance and conductance measurements

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over a wide temperature range (20–180 °C), and in various dielectric mediums (*e.g.* air, epoxies). In addition, the multifunctional MSP was successfully applied for *in situ* and real-time monitoring of epoxy polymerization. The measurements from the MSP indicated the different stages of these processes as confirmed by a reference measurement using a commercial impedance analyzer. This work opens up new design opportunities for impedance sensing devices.

2. Experimental

2.1. Fabrication of the MSP

The fabrication process starts from micro structuring a copper pattern on a flexible PI-Cu (UPISEL-N BE1410, UBE Inc., Japan) substrate *via* photolithography and wet etching. Then, a flexible circuit coverlay with an adhesive layer was laser cut, and laminated on the micro structured circuit at 120 °C. Afterwards, organic solderability preservative was applied to the copper surface. The lead-free solder paste (DP5505, Interflux, material: Sn96.5Ag3Cu0.5) was dispensed manually using a dispensing system (UltraSaver, EFD Inc, USA) and the chips were assembled manually, and they were afterwards soldered in a reflow oven (IBL SLC300, Siemens). The interdigital sensor (IDS), the calibration unit and the temperature IC (LMT87, Texas Instruments, USA) were built around a MCU (ATmega1280, Atmel, San Jose, USA) with an internal 10-bit analog to digital converter (ADC). A temperature insensitive SMD capacitor of 22 pF (1% precision, 0 temperature drift) was connected to MCU as the calibration unit.

2.2. In situ *monitoring of two epoxies*

Two epoxy systems were studied. The epoxy system (Sicomin, Châteauneuf-les-Martigues, France) is a two-part system comprising the resin (SR8500) and the hardener (SZ8525). The epoxy system (Momentive, Waterford, NY, USA) is a two-part system comprising the resin (EPIKOTE MGS RIMR 135) and the hardener (EPIKURE MGS RIMH 137). For both epoxies, 100 g of resin and 30 g of hardener were thoroughly mixed and degassed. A MSP, a reference IDS (design: $W = g = 100\,\mu$m, $L = 15$ mm, and 40 fingers) and a reference thermocouple (type K) were placed closely together on a polydimethylsiloxane mould. Afterwards, the resin mixture was slowly poured into the mould until completely covering the MSP, the reference IDS, and the thermocouple. RIMR135 resin was cured for 40 h at room temperature (22 °C), SR8550 were cured at 70 and 90 °C. An HP 4284A Precision LCR meter performed the impedance measurement of the IDS with frequency sweep ranging from 100 Hz to 1 MHz with 10 points per decade. A thermocouple data logger TC-08 (Pico Technology, UK) was used for the temperature measurements. The time required per sweep was 5 s for the MSP, 16 s for the LCR meter, and 5 s for the thermocouple data logger.

3. Design of the miniaturized sensor patch (MSP)

3.1. System overview

Novel impedance sensing devices are aimed to be applied in-field or in-body to permit real-time and *in situ* monitoring functionalities. Hence, for these types of devices to be useful, compact designs with integrated readout are desirable. Fig. 1a shows an example of *in situ* structural health monitoring of a polymeric composite material using the MSP, where different sensors are integrated in a single platform for multifunctional sensing, such as impedance (capacitance, conductance) and temperature measurements. The sensor patch should be flexible, small-sized, and light-weight to minimize its disturbance to the integrated structure [23–25]. Fig. 1b illustrates the system-level block diagram of the proposed MSP. The MSP uses an interdigital sensor (IDS) employing a readout circuitry and a calibration unit for accurate impedance measurements and a commercial temperature IC for temperature measurement. The IDS, the calibration unit and the temperature IC are built around a microcontroller unit (MCU) with a 10-bit analog to digital converter (ADC). Thanks to the on-board MCU, virtually all commercial sensor ICs can be incorporated to the MSP to further extend its functionalities. An on-board multiplexer (MUX) switches between the IDS and calibration unit to the ADC. The microcontroller's serial communication capability is used to transmit the data to the PC's virtual serial port through USB. The MSP is powered by an external voltage source of 5 V. Its power consumption depends on the MCU in use. The MCU in its present setup consumes 10 mA, with an input voltage of 5 V and running at 8 MHz, as stated in the datasheet. A photograph of the fabricated MSP, with a size of 24 mm × 20 mm, is shown in Fig. 1c.

The flow chart of the overall measurement scheme of the MSP is illustrated in Fig. 1d. First, the MCU is initialized with hardware configurations. Then, the program selects the first channel, i.e. the channel with the IDS. The program reads the ADC value and stores it in the data register; next, the program selects the second channel, the one with the calibration unit, and the same procedure is repeated. Afterwards, the program proceeds to the temperature measurement IC. Finally, all the data are sent to the PC in one go, and the MCU loops back after a programmed delay. One complete cycle takes about 5 s, which is programmable depending on the actual measurement scenario. Further details on the impedance measurement is discussed in next section.

3.2. Operating principles of the impedance measurements

3.2.1. Modelling of the impedance readout circuitry

We propose a simple yet effective readout circuitry capable of rapid and accurate capacitance and conductance measurements over a wide temperature range (20–180 °C), and in various dielectric mediums (*e.g.* air, epoxies). Fig. 2 depicts the operating principle of the impedance measurement of the MSP. The readout circuitry (Fig. 2a), termed the bridge in this article, is built around the MCU. The upper side of the bridge represents the IDS with a capacitance of C_{MUT}, and the lower side represents a reference capacitance of C_S. The lossy part of the capacitor is modeled as a parallel resistor, where R_{MUT}, R_S is the lossy part of C_{MUT} and C_S, respectively. An interdigital sensor, as shown in Fig. 2b, operated in the fringing electric field mode as demonstrated by the finite element modelling, is designed for impedance sensing. In an IDS structure, L, W, g, N, η, stands for the length of the finger, width of each finger, the spacing between fingers, the number of fingers, and the metallization ratio ($\eta = W/(W+g)$), respectively. These geometrical parameters are important factors that influence the sensor's nominal value and sensitivity [26]. In the section 'design consideration', further details on how to select the design parameters will be discussed. We start with both capacitors discharged and both input and output pin at 0 V. When a voltage, $v_{IN}(t)$, is supplied at the input, a current will flow through both capacitors. $v_{IN}(t)$As a result, the output voltage, $v_{OUT}(t)$, will respond in accordance to $v_{IN}(t)$. $v_{OUT}(t)$ is a function of, $v_{IN}(t)$, C_{MUT}, C_S, R_{MUT}, and R_S. By establishing the input-output relationship of the system, the system parameters of the circuit can be extracted. Here, the circuit is first analyzed in s-domain using Laplace transform for the sake of simplicity [27], and then converted to time domain using inverse Laplace transform. From Kirchhoff's current law, we have:

$$sC_{MUT}(V_{IN} - V_{OUT}) + \frac{V_{IN} - V_{OUT}}{R_{MUT}} = sC_S V_{OUT} + \frac{V_{OUT}}{R_S} \qquad (1)$$