M. F. Porto Cruz*, E. Fiedler, O. F. Cota Monjarás, and T. Stieglitz

Integration of temperature sensors in polyimide-based thin-film electrode arrays

Abstract: Continuous monitoring of the tissue temperature surrounding implantable devices could be of great advantage. The degree and duration of the immune activation in response to the implant, which is responsible for signal deterioration, could be inferred from the associated temperature raise and the heating caused by electrical or optogenetical stimulation could be accurately controlled. Within this work, a thin-film platinum RTD embedded in polyimide and a readout system based on the Wheatstone bridge configuration are presented. The RTD offers a sensitivity of 8.5 $\Omega\cdot{\degree\text{C}}^{-1}$ and a precision of 4.1 $\Omega$. The accuracy of the complete system calibrated for temperatures ranging from 34 to 41 $\degree\text{C}$ lies between the classes A and B defined by the standard IEC 751, which correspond to tolerances of $\pm0.22$ and $\pm0.48 \degree\text{C}$ at 37 $\degree\text{C}$, respectively.

Keywords: temperature sensor; polyimide; electrode-array

DOI: 10.1515/CDBME-2015-0126

1 Introduction

Implantable neural probes such as cochlear implants and deep brain stimulators have been successfully commercialized for the treatment of hearing impairment, Parkinson’s disease, epilepsy and several other neurological disorders [1]. A crucial challenge faced by their implantation is the inflammatory response triggered by the surrounding tissue [2], which is believed to be the main reason for signal deterioration [3]. Since immune activations are accompanied by an elevation of the tissue temperature, varying from slight temperature increases to high states of fever [4], the integration of temperature sensors in implantable probes allows inferring the degree and duration of the inflammation response. Furthermore, in case of optogenetic probes, temperature monitoring is additionally useful as it enables to control the heating of the tissue exposed to the emitted light [1, 3]. Moreover, since the body temperature is a vital sign that characterizes basic body function, the information given by the sensors provides assessment to the general health state of an individual after the inflammation period.

A thin-film platinum resistance temperature detector (RTD) embedded in polyimide is hereby addressed for continuous monitoring of the tissue temperature. Platinum offers a high linearity, accuracy and stability [5] among other commonly used metals and, furthermore, it is highly resistant to oxidation and corrosion (noble metal), being successfully used in biocompatible devices. In respect to the encapsulation material, polyimide stands as a suitable material due to its excellent thermal [6] and chemical stability, good dielectric properties [1] and, more importantly, high flexibility, which allows minimizing the mechanical mismatch between the implant and the tissue [7]. The RTD operation should not cause any damage on the surrounding tissue or itself. Therefore, its excitation should be performed by a charge-balanced biphasic pulse in order to ensure the reversibility of the redox reactions that occur at the tissue-sensor interface, preventing adverse long-term effects.

Within this work, thin-film RTDs were designed and fabricated and a readout system was developed, which comprised a 3-wire Wheatstone bridge for detection of resistance changes and a microcontroller for excitation of the bridge and digitalization of the modulated output signal. A 7-segment indicator was implemented to display the temperature value in real time. The readout system was assembled on a PCB and optimized for temperatures ranging from 34 to 41 $\degree\text{C}$, which corresponds to the temperature interval that typically guarantees paired thermoregulation abilities in an individual [4].

2 Material and methods

Thin-film platinum RTDs embedded in polyimide were designed, fabricated and characterized. A readout system based on the Wheatstone bridge configuration was developed and calibrated for temperatures ranging from 34 to 41 $\degree\text{C}$. 


2.1 RTD design and fabrication

The RTD was designed as a meander track: 13 \( \mu \m\) wide, 300 nm thick and approximately 100 nm long. Due to the small section area, the thin-film meander layout allowed achieving a high nominal resistance for a small surface area.

Several RTDs were fabricated by MEMS processing in a class 100 cleanroom, following the steps described elsewhere for the fabrication of thin-film electrodes [8]: the process started by the deposition of a 5 \( \mu \m\) polyimide layer (U-Varnish-S, UBE, Tokyo, Japan), followed by the evaporation of a 300 nm platinum layer which was subsequently patterned by lift-off to form the meander. A second 5 \( \mu \m\) polyimide layer was deposited and the contact openings and sensor outlines were patterned by reactive-ion etching (RIE).

2.2 Hardware

The Wheatstone bridge offers two favorable features: it provides a relative measurement, ensuring high sensitivities, and it offers good common mode rejection. Since the RTD will be ultimately implanted in the tissue, behaving as a remote varying-element, the 3-wire bridge (Figure 1) was chosen as the most suitable approach. In comparison to the typical quarter bridge, this configuration minimizes the resistive effect of the two leading wires connecting the RTD to the rest of the bridge (\( R_{LW} \)) [9]. Considering \( R_3 = R_4 \), the output equation of the 3-wire bridge may be written as:

\[
V_{OUT} = \frac{V_{IN}}{2} \left[ \frac{R_{RTD} - R_{REF}}{R_{RTD} + R_{REF} + 2 \cdot R_{LW}} \right]
\]

where \( V_{OUT} \) and \( V_{IN} \) stand for the output and applied voltage, respectively. \( R_{RTD} \) ranges from a minimum to a maximum resistance value correspondent to the lowest and highest temperature of the considered range, respectively. To the extent of maximizing the sensibility of the readout system, \( R_{REF} \) was defined as the lowest value of the \( R_{RTD} \) range, in order to achieve a \( V_{OUT} \) sweep from zero (\( R_{REF} = R_{RTD} \)) to a maximum positive value correspondent to the maximum deviation of \( R_{RTD} \) from \( R_{REF} \) (\( R_{RTD} > R_{REF} \)).

A 1 kHz square wave was generated by the microcontroller PIC24F16KA301 and applied to the input terminal of the 3-wire bridge (\( V_{IN} \)). The signal was centered at the reference voltage \( V_{REF} \), correspondent to half of the supply voltage, by means of an AC coupling capacitor \( C_{COUP} \). The resistor \( R_I \) allowed setting \( V_{IN} \) and, consequently, the current flowing through the bridge, which was set to 50 \( \mu \m\).

The instrumentation amplifier INA826 provided a differential signal that was smoothed by a passive RC low-pass filter (\( f_c \approx 16 \mK\)) and subsequently digitalized by the 12-bit ADC of the microcontroller. The digital results were processed, converted into temperature values and finally displayed in real time on the QDSP-60647 7-segment indicator.

The display was a 4-digit common cathode indicator. The four cathodes were activated one at a time, being multiplexed by the microcontroller at 889 kHz to ensure that the four digits were legible simultaneously without perceptible flickering. The seven segments and the decimal point, which corresponded to eight anodes in total, were also controlled by the microcontroller, which performed the BCD to 7-segment conversion. The active cathode was set low, while the anodes required to display the numeral were set high.

The system was assembled on a PCB of 2.2 by 3.7 cm. The precision of the readout system depended on how well the INA output signal was optimized to cover the ADC input voltage range (0-3.3 V). The optimization started with the determination of \( V_{IN} \), which was given by the product of the equivalent resistance of the bridge and the current defined by \( R_I \) (50 \( \mu \m\)). Since \( R_{RTD} \) was a varying quantity and \( R_{REF} \) was defined as the lowest \( R_{RTD} \) value, the equivalent resistance of the bridge was only an estimate value dependent on the considered temperature range. The range was defined from 34 to 41 \( ^\circ \mC \) (\( R_{REF} \) equaled \( R_{RTD} \) at 34 \( ^\circ \mC \)) as it represents the temperature interval that normally ensures paired thermoregulation abilities in an individual [4]. By plugging \( V_{IN} \) in the output equation of the bridge and replacing \( R_{RTD} \) by its maximum value (\( R_{RTD} \) at 41 \( ^\circ \mC \)), the maximum \( V_{OUT} \) was determined. Finally, the gain of the INA (set by the gain resistor \( R_G \)) was given by the quotient of the ADC input voltage range by the maximum \( V_{OUT} \).

2.3 Software

The temperature readout was coded in an amplitude modulated square wave as shown in Figure 1.

In order to generate the 1 kHz square wave, an output pin of the microcontroller was programmed to toggle at every match of a timer counter (\( OutPin \) timeline). The modulated square wave returned by the INA826 was being periodically sampled by the ADC’s sample and hold circuit (\( Sampling \) timeline) and in the middle point of each phase a conversion was performed, yielding two samples per period (\( Conversion \) timeline). The final digital result was given by the difference between the two values and, thereby, it represented a peak-to-peak amplitude (\( R_A \) and
M. F. Porto Cruz et al., Integration of temperature sensors in polyimide-based thin-film electrode arrays

Figure 1: Schematic of the developed readout system (left). Time diagram summarizing its software operation (right)

Figure 2: RTD characteristic curve from 0 to 100 °C (n=5) given by a second order polynomial fit (dashed line). Theoretical curve given by the Callendar-Van Dusen equation (solid line).

\[ R_T(T) = R_0 (1 + A T + B T^2) \]

where \( A \) and \( B \) are constants. The measured data fits the statistical model (second order polynomial) with a coefficient of determination (R-squared) of 0.9997. The sensitivity of the RTD, given by the first derivative of the polynomial fit, was around 8.5 \( \Omega \cdot °C^{-1} \) at 37 °C, close to the standard sensitivity of 8.6 \( \Omega \cdot °C^{-1} \) given by the Callendar-Van Dusen equation also at 37 °C ([10]). The precision, given by the average standard deviation (average of the differences between real and expected values), was ± 4.1 \( \Omega \) (55 measurement points).

After calibration of the readout system, the digital results yielded by the five measurements (n=5) were converted into temperature values. The tolerance of each measurement point, given by the difference between the

\[ S_{th} = \frac{dR_T}{dT} \]

were registered every 10 °C. Five measurements were performed.

Secondly, the developed readout system was calibrated as measuring system itself. The temperature was slowly increased from 31 to 41 °C and, afterwards, the hot-plate was turned off to let the temperature decrease from 41 to 34 °C. Samples were saved every 0.5 °C in the EEPROM of the microcontroller for both increasing and decreasing periods to the extent of investigating the possible occurrence of hysteresis. Five measurements were performed.

3 Results

The resistance values yielded by the five measurements (n=5) performed with the LCR-meter from 0 to 100 °C were consistent with the theoretical curve given by the Callendar-Van Dusen equation (Figure 2) according to the standard IEC 751 (A=3.9083×10^{-3} °C^{-1} and B=−5.775×10^{-7} °C^{-2}) [10]. For the theoretical curve, \( R_0 \) was calculated as the geometrical resistance of the RTD at 0 °C (\( R_0 =2227.4 \Omega \)) considering the practical resistivity of platinum evaporated on polyimide, which was previously determined as 8.7×10^{-8} \( \Omega \cdot m \) at 0 °C. The measured data fits the statistical model (second order polynomial) with a coefficient of determination (R-squared) of 0.9997. The sensitivity of the RTD (S), given by the first derivative of the polynomial fit, was around 8.5 \( \Omega \cdot °C^{-1} \) at 37 °C, close to the standard sensitivity of 8.6 \( \Omega \cdot °C^{-1} \) given by the Callendar-Van Dusen equation also at 37 °C (\( S_{th} \)). The precision, given by the average standard deviation (average of the differences between real and expected values), was ± 4.1 \( \Omega \) (55 measurement points).
practical and reference temperature, was calculated (Figure 3). The average tolerance was ±0.11 °C (149 measurement points). According to the standard IEC 751, the accuracy of the readout system lays between the classes A and B, which correspond to tolerances of ±(0.15+0.002·T)°C and ±(0.30+0.005·T)°C, respectively. Hysteresis could not be observed.

Figure 3: Accuracy plot given by the tolerance of each measuring point. The accuracy classes A and B given by the standard IEC 751 are presented as shaded regions.

The system had a power consumption of 33 mW with display and 20 mW without display. The TLC277 operational amplifier used to set \( V_{\text{REF}} \) consumed from 1.4 to 3.2 mA, the bridge consumed around 100 µA (50 µA per arm), the INA826 operated at 200 µA, the microcontroller consumed down to 8 µA in run mode and the display consumed an average of 500 µA per segment.

4 Discussion and conclusion

The fabricated RTD had a sensitivity close to the standard sensitivity given by the Callendar-Van Dusen equation. The offset between the theoretical and characteristic curve (Figure 2) is explained by the mismatch between the real and geometrical resistance of the platinum meander (2310.7 and 2227.4 Ω, respectively) due to fabrication tolerances.

The average standard deviation (4.1 Ω) was affected, not only by the behavior of the RTD itself, but also by the imprecision of the calibration setup. Since the working space was at room temperature (temperature gradient between air, water and hotplate) and the used hotplate had no feedback mechanism, the temperature had to be abruptly changed in order to provoke the desired temperature increase or decrease in due time. A ramp temperature profile was difficult to achieve and, consequently, the water temperature was barely stable throughout the measurements.

The average temperature error introduced by the readout system (±0.11 °C) laid in the accuracy class A (Figure 3). For comparison, the LM35 series of temperature sensors from Texas Instruments (Dallas, Texas, United States) ensures an accuracy of ±0.5 °C at 25 °C (class B). The calculation of the error relied on the values given by the reference thermometer, whose precision was also affected by the imprecision of the calibration setup, leading to a decrease in accuracy. Moreover, a temperature range from only 31 to 41 °C was considered, for which the relative impact was more notorious due to the smaller temperature step between measurements.

Although minimum power consumption was not taken as primary concern while developing the readout system (total power consumption of 33 mW), all the elements constituting the system offered low power demands, with the exception of the TLC277 operational amplifier, which could be eventually replaced by a low power version such as the LT1097.

In order to improve the readout system calibration, the ramp temperature profile should be replaced by a step profile, which would ensure a stable temperature for each measurement. Such a profile could be achieved by placing the setup inside an oven or, more roughly, by using a hotplate with feedback mechanism. By these means, the real accuracy of the developed measuring system could be determined, which is believed to be higher than ±0.11 °C.

In conclusion, a robust temperature measuring system to monitor tissue temperature was developed. Temperature raises due to electrical and optogenetical stimulation (up to 10 °C) [11] or vasodilatation and increased metabolism (2 to 3 °C) [12] could be accurately detected.

Acknowledgment: Research supported by the German Federal Ministry of Education and Research (BMBF grant 01GQ0830) and by BrainLinks-BrainTools, Cluster of Excellence (DFG, grant no. EXC1086).

Author’s Statement

Conflict of interest: Authors state no conflict of interest.

Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.
References