Conformal Devices for Thermal Sensing and Heating in Biomedical and Human–Machine Interaction Applications

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Thermal ablation has been adopted as one of the most common cancer treatment approaches in medical surgery. By increasing the temperature (>50 °C) on the cells, the cells are destroyed because of denaturation. Herein, an ultrathin Archimedean spiral pattern heater/sensor technology is introduced which can perform ablation by attaching conformally onto the organs for precise heating and temperature sensing. In the heater mode, the heater temperature is linearly proportional to the input joule heating power up to 400 mW. In the sensor mode, the temperature of the conformal metal wire is also linearly related to the resistance by the temperature coefficient of resistance (TCR). The conformal heater to perform ex vivo ablation on the porcine liver is utilized. By further integrating the devices with robotic palm and perform heat-and-sense interactions, a human–machine interface (HMI) apparatus is demonstrated which can be potentially applied in surgical robots or other tactile stimulation systems.

1. Introduction

Flexible electronics for health monitoring have been one of the leading directions in the development of healthcare devices. Ultrathin devices with a few micrometer thickness can offer excellent conformality and promising performances in measuring physiological signals. Compared with traditional electronics with rigid substrates, flexible devices can minimize the mechanical mismatch, irritation, and discomfort on the subject under test. In addition, the conformality of the devices can also acquire better signal-to-noise ratio (SNR) by the significant reduction of the contact impedance. To date, various types of flexible sensors have been developed for biomedical and conformal applications. Sensors for physical signals such as body temperature, artery pressure, and blood pressure and electrical signals such as electrocardiography (ECG), electromyography (EMG), and electroencephalography (EEG) have been demonstrated. Ultrathin sensors with a total thickness of 630 nm have been integrated onto a medical catheter to monitor the inflammation level of the patient in real time. Apart from the sensing functions, flexible electronics have been applied in the human–machine interface (HMI) devices with feedbacks. Recently, Yu et al. have developed mechanical vibratory tactile device on the human skin which can mimic the touch feeling virtually. Dejac et al. have utilized gallium-based strain sensor to detect the body motion in virtual-reality scenario. On the surgical tool side, tactile sensors integrated with the da Vinci surgical robots have been reported by different groups. Among all these applications, conformal devices combining heating and sensing together have not been fully investigated even it will have tremendous potentials in surgical robots. This additional thermal data can provide more comprehensive information of the organs for the surgeons to decide the most suitable therapeutics. In the current work, we present Archimedean spiral gold wire which can be used as a conformal heater as well as temperature sensor on different organs and epidermis. Several mechanics designs have been reported such as serpentine and circular and demonstrate promising results. Nevertheless, Archimedean spiral exhibits higher stretchability (200%) compared with serpentine design (98–112%) under the same areal coverage and contour length. However, in circular design, the sharp turnings in each of the half-loop of the circle may induce weak points. Potential breakdown of electrode may result when the device is stretched or under high current. Nonetheless, the spiral maintains circular pattern in all orientation and can avoid the potential weak points. Archimedean spiral hence demonstrates better mechanical design in serving as sensor/heater compared with the reported works. By performing photolithography on the 1.5 μm parylene, spiral pattern metal traces with 20 and 40 μm width and 55 nm thickness are developed. The overall area of the device is down to 12.6 mm². The thin parylene provides decent mechanical properties, including low bending stiffness and high surface energy adhesion, which can ensure conformal contacts. As the air gaps between the device and the targeted tissue are eliminated, this contact reduces measurement noise and enhances heat transfer. The temperature coefficient of resistance (TCR) and joule heating effects of the devices are examined in detail. The metal trace can heat up to 60 °C,
which is already adequate for biological ablation or to perform hyperthermia.[21,22] By fitting the measured temperature profile with the analytical model, the thermal diffusivity ($\alpha$) and conductivity ($k$) of porcine liver are evaluated to be $1.51 \times 10^{-7}$ m$^2$ s$^{-1}$ and 0.504 W m$^{-1}$ K$^{-1}$, respectively. In our advanced human–robotic thermal feedback system, the response time needed to transfer the heat being sensed by the robotic palm to the heater attached on nitrile glove is around 10 s.

2. Device Structure and Operation

The thin heater/sensor consists of thin metal traces (5 nm Cr/50 nm Au, with 20 and 40 μm width) is patterned by photolithography in the geometry of Archimedean spiral pattern with interconnects for external wiring (Figure 1a,b). The device is deposited on a 1.5 μm thick layer of parylene and encapsulated by another 500 nm parylene. The TCR is given by

$$\frac{\Delta R}{T} = \alpha R$$

(1)

where $R$, $T$, and $\alpha$ are the resistance, temperature, and TCR of the metallic element, respectively. The spiral pattern, due to its geometric property, can possess high length-to-area ratio and ensure a relatively high resistance. The length of the Archimedean spiral pattern can be calculated by Equation (2) (see Figure S1, Supporting Information, for the deduction).

$$L = 2 \int_0^{2\pi} \sqrt{\left(\frac{r + r_0 - r_{oi}}{2n\pi}\right)^2 + \left(\frac{r_0 - r_{oi}}{2n\pi}\right)^2} \, d\theta$$

(2)

where $\theta$, $r_0$, $r_{oi}$, and $n$ are the angle radian, inner radius, outer radius, and number of loops of the Archimedean spiral pattern, respectively (see Figure S1, Supporting Information, for detailed explanation for each parameter). Figure 1c,d shows the optical and magnified images of the devices. Two patterns with different number of loops (6.2 and 12.4), width (20 and 40 μm) and pitch distance (40 and 120 μm) were fabricated in the current work and the radii of the both patterns are 2 mm. The 6.2 and 12.4 loops devices are known as the sparse and dense device, respectively. The estimated length of the two patterns are 7.87 and 15.7 cm with resistance 2109 ± 10 Ω and 7500 ± 10 Ω, respectively. The higher $R$ (>1 kΩ) can offer larger variation ($\Delta R$) for the same TCR and consequently improves the SNR.

First, the device was demonstrated as temperature sensor (sensor mode) and heated up to a temperature ranging from 25 to 90 °C. The temperature and resistance of the device were measured by infrared (IR) camera and sourcemeter simultaneously. As shown in Figure 2a,b, the resistance and temperature show linear relationship ($R^2 > 0.999$) for both metal trace patterns. The variation of resistance is around ±10 Ω and the variation of temperature is around ±1 °C. The spatial resolution of device in temperature sensing is 4 mm, which is the same as the diameter of the device. The sensitivity of the temperature sensor can be derived by the slope of the graph (with $R^2 > 0.999$) in Figure 2a,b. The sensitivities of the devices are found to be 5.69 Ω K$^{-1}$ (Figure 2a) and 18.5 Ω K$^{-1}$ (Figure 2b), respectively. Furthermore, as shown in Figure 2c,d, the variation of the TCR in the whole operating temperature range is within 5%. The values are consistent with the reported values for thin gold films (0.0025–0.0034 K$^{-1}$).[24–27]

Although the device serves as heater (heating mode), the joule heating effect can be described as

$$T \propto P = I^2 R$$

(3)

where $T$, $P$, $I$, and $R$ are the temperature, power input, electrical current, and resistance, respectively. The relationship between temperature and the resistances is shown in Figure 3. Figure 3a,b compare the temperature and resistance relationship in sensing and heating modes. The resistance offset in the

![Figure 1](image-url)
heating mode is attributed to extra thermal mass of the object beneath the heater, which requires the heater actually goes up to a higher temperature. The spatial resolution of heater is 4.6 mm which is limited by the size of the device and the spatial resolution of the IR camera. The device temperature also shows linear response ($R^2 > 0.999$) with input power (Figure 3c,d) and both patterns can achieve higher than 50 °C with low power input (300 mW), whereas conventional radiofrequency (RF) thermal ablation may require 50 W or higher to achieve the same temperature.\[28\] This has indicated the device capability serving as an ablative tool to perform hyperthermia and thermal ablation especially at the surfaces of the organs.

2.1. Device Conformity Study

Before we perform the ablation test, we want to ensure the ultra-flexible devices can really provide a conformal contact with the animal organs. A conformal contact can be achieved between the thin film and the object by meeting\[29\]

$$\gamma > \frac{B}{2r^2}$$  \hspace{1cm} (4)

where $\gamma$, $B$, and $r$ are the adhesion energy per unit area between the thin film and the object, bending stiffness of the film, and radius of curvature of the object, respectively. The adhesion energy for biological organ with biofluid $\gamma_{\text{organ}}$ ranges from 75 to 150 mJ m$^{-2}$.\[29\] The bending stiffness calculated from Figure S3, Supporting Information, is 819 μJ m$^{-2}$ and hence satisfies in Equation (4). This implies the whole device can fully wrap on the porcine liver organ naturally. Figure 4 shows the laminations of the devices onto the human skin and porcine liver. As expected, the device can conformally attach on these organs. Based on the $\gamma_{\text{organ}}$ equals 150 mJ m$^{-2}$, the device with around 2 μm total thickness and corresponding bending stiffness $B = 4.10 \text{ N m}^{-1}$ can fully wrap on the biological organ with radius of curvature down to 120 μm.

2.2. Ex Vivo Experiment on Thermal Ablating Porcine Liver

Thermal ablation experiment was carried and verified by simulation models. The device was laminated on porcine liver tissue and applied with power input. Figure 5b,c shows that heater temperature can increase up to 54.9 °C and lesion is observed after 10 min ablation. The lesion is defined as the region where has undergone 45 °C. For most of the mammal organs, due to the denaturation of proteins, the color opacity increases when the temperature is between 45 and 67 °C.\[30\] Because of the evaporation of the water in the porcine liver during ablation, a device mark can be observed in Figure 5b. In addition, the region where laminated...
with device kept the water moisture, whereas other regions became less moist as they were exposed to ambient air. Using a 1D analytical solution and a large area heater, as shown in the Supporting Information, the thermal diffusivity ($\alpha$) and thermal conductivity ($k$) are extracted to be $1.51 \times 10^{-7} \text{ m}^2 \text{s}^{-1}$ and $0.504 \text{ W m}^{-1} \text{ K}^{-1}$, respectively, and which are comparable with reported values.$^{[31–34]}$ After knowing the $\alpha$ and $k$, the lesion depth calculated by a finite element simulation is 2 mm which agrees well with the experimental result (Figure S2f, Supporting Information). The lesion depth depends on the surface temperature of the heater for given thermal conductivity and boundary conditions of the porcine liver. As the heating temperature is linearly related to the electrical power (Figure 3c,d), the depth of lesion can be precisely controlled by inputting the corresponding electrical power. In the finite element model, material properties such as Young’s modulus and Poisson’s ratio were obtained from

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**Figure 3.** Performances of the devices in sensing and actuation mode. a,b) Resistance against temperature in sensing and actuation mode. c,d) Heating temperature with respective electrical power input. e) IR image, overlapped with optical image, after power input.
Figure 4. Optical images illustrating conformity of the devices. a,b) Optical and magnified image of the device conformal on human skin. c,d) Optical and magnified optical image of the device laminating on porcine liver.

Figure 5. Optical images illustrating thermal ablation of the devices. a) The optical image of device laminating on porcine liver. b) The optical image of porcine liver after 10 min thermal ablation. Lesion, which is same size as the device, is observed. The device mark is also formed at the surrounding due to the evaporation of moisture in other unlaminated region. c) IR image of devices laminating on porcine liver during thermal ablation. The ablation temperature can rise up more than 50 °C. d) The cross-section of the ablated porcine liver. A lesion depth of 2 mm is observed.
The boundary conditions were set to be constant heat flux at the interface between the heater and liver, whereas other boundary conditions were set to undergo natural convection with coefficient $h = 0.5 \text{ W m}^{-2} \text{ K}^{-1}$. In practical situation, perfusion of blood will induce temperature drop in the tissue during thermal ablation. The effect of perfusion is similar to the water flow experiment discussed in Figure S4, Supporting Information.

### 2.3. HMI for Thermal Sensing and Actuation

The conformal sensor/heater is brought to a practical application by integrating with robotic system. Herein, the integration of thermal sensor on the finger of the robotic palm and thermal actuator on nitrile gloves is trying to mimic the thermal interaction between robots and humans. Figure 6a,c shows the thermal sensor laminated on robotic finger and the optical images and IR images of robotic palm grasping a bottle of water at 43°C. Figure 6d,e,h,i shows the laminated thermal actuator on standard laboratory nitrile gloves. The 200 μm-thick laboratory nitrile glove allows direct and fast heat transfer from the heater to human skin. The wore glove shows a higher temperature rise compared with empty glove with the same electrical power input because of the base line temperature from human body compared with ambient air (Figure 6f,g,j,k).

The device, which served as thermal sensor, was laminated on the finger of the robotic palm. The robotic palm was programmed to grasp a bottle at designated temperature. The resistance of the device and the water temperature were recorded by sourcemeter and infra-red camera simultaneously. On the other hand, the device, which served as thermal actuator, was laminated on a nitrile glove. A LabVIEW program was developed to transform the temperature of the object measured by the thermal sensor, into corresponding electrical input power of the heater on the glove which is able to heat up the glove to the same temperature. As shown in Figure 7, when the robotic palm grasps the object with temperature, the thermal sensor will give the corresponding resistive change. This resistance information is recorded and processed by the computer program. In the program, the resistance against temperature of the sensor, because it is linear, can be described by

$$R_s = m_s T_s + c_s$$

where $R_s$, $m_s$, $T_s$, and $c_s$ are the resistance, slope, sensing temperature, and $y$-intercept of the resistance–temperature curve of the thermal sensor. The slope $m_s$ is proportional to the TCR and

![Figure 6](image_url)

**Figure 6.** Optical and IR camera images showing the devices laminated on robotic finger and nitrile glove. a) Device laminated on the robotic gripper serving as thermal sensor. b) Robotic hand gripping a bottle of hot water with digital thermometer reading. c) IR camera image of the grasping action. d–g) Optical image and IR camera image of the device laminated on empty nitrile glove serving as thermal actuator. h–k) Optical image and IR camera image of the device laminated on wore nitrile glove serving as thermal actuator.
inverse proportional to the resistance (at ambient temperature) of the metal traces. In contrast, the resistance against temperature of the thermal actuator, as it is also linear, can be described by

$$T_h = m_h P + c_h$$

(6)

where $T_h$, $m_h$, $P$, and $c_h$ are the heating temperature, slope, power input, and $y$-intercept of the temperature–power curve of the thermal actuator. The slope $m_h$ is dependent on the thermal mass and baseline temperature of the object underneath the device. A larger thermal mass will result in smaller $m_h$, whereas a higher baseline temperature will result in a larger $m_h$. Because the thermal actuator has to heat up to the same temperature recorded by the sensor, Equation (5) is substituted into Equation (6) by equating $T_s = T_h$. The power input required in the thermal actuator can be calculated based on sensor resistance by

$$P = \frac{R_s - c_h}{m_h}$$

(7)

By switching the input from power to the voltage, Equation (7) can be further modified into (see Figure S5, Supporting Information, for the deduction)

$$V = \sqrt{\frac{m_h (R_s - c_h)^2 + (m_h - m_s) (R_s - c_h) - c_h c_s}{1000}}$$

(8)

where $V$ is the voltage required for actuator to achieve the same temperature and $R_s$ is the sensing resistance in sensor. The details can be seen in the Supporting Information. By fitting the curve in Figure 3a,b, Equation (7) becomes $P = 0.365 R_s - 3025$ and Equation (8) becomes $V = \sqrt{0.0001 R_s^2 - 0.88 R_s + 400}$, respectively.

Figure 7a,b shows the images of the remote thermal sensor on robotic finger and the thermal actuator on the nitrile glove, respectively, illustrating the thermal interaction. When the robotic palm grasped the object, the heating temperature of the thermal actuator on the glove can reach to a close temperature value (Figure 7c) in a short time (around 10 s). Once the robotic palm released, the thermal actuator temperature dropped to the body temperature (around 10 s) as shown in Video S1, Supporting Information. This system can serve as a virtual thermal sense for glove wearer. Figure 7d shows the potential integration of the device onto the surgical robot. The system is controlled by a human operator, that is, the surgeon, inside a console to perform minimally invasive surgery. The heat-and-sense interaction, as shown in Figure 7a–c, can provide virtual thermal sense to the surgeon on the target organ region. Furthermore, as the device can be operated in heater mode, the device attached onto the surgical tool can serve as thermal ablative tool to perform hyperthermia or thermal ablation.

3. Discussion

We presented the patterning process, mechanical and materials design to develop a conformal thermal sensor and heater. The device demonstrates linearity ($R^2 > 0.999$) in both sensing and heating within 25–60 °C, which is the temperature range of thermal ablation. This sensor/heater feature provides the potential use in tissue temperature monitoring and thermal ablation. Because of the conform design (2 μm device thickness), both experiments and calculations show that the whole device exhibits...
The Young's modulus and Poisson's ratio were measured as 82 GPa and 0.25, respectively. The small size of the device (12.6 mm²) allows the monitoring of tissue temperature and localized thermogenesis. It also gives less invasiveness in thermal ablating the organ by having localized heating with temperature up to 55 °C. Lesion depth of 2 mm can be achieved under 10 min ablation. Moreover, further research in heat-resistant substrate/encapsulation material is expected to develop higher temperature (>110 °C) applications. Miniaturization of the device and integration with other medical tool, such as catheters and endoscopes, to monitor local thermogenesis and perform thermal ablation in cellular level are the expected future aspects of the work. Heat-and-sense interaction is demonstrated by attaching thermal actuator and sensor in nitrile glove and robotic palm, respectively. The temperature response time (around 10 s) in heat-and-sense interaction allows the potential application in providing thermal feedback in the da Vinci surgical system.

4. Experimental Section

Fabrication of the Archimedean Spiral Pattern: Fabrication began with depositing polymeric layers (specially coating systems) layer (1.5 µm) on precleaned glass (25 mm × 25 mm × 1 mm) by chemical vapor deposition (CVD). Positive photoresist AZ® iLOF 2020 (MicroChemicals) was spin-coated on the substrate and followed by UV curing with respect to the Archimedean spiral pattern. Thermal evaporation defined the layers of Cr (5 nm) and Au (50 nm) into a thickness suitable for use as sensing/heating element. The thermal deposited devices were immersed into dimethyl sulfoxide (DMSO) solution to complete lift off process. Silver paste was smeared onto interconnects and connected with extended thin copper wire (13 µm). Parylene layer (500 nm) was deposited on top of the device to serve as a passivation layer using CVD.

Electrical and Thermal Characterizations of Thermal Sensor and Thermal Actuator: The sensor was put on hot plate with increasing temperature. The temperatures of sensor were measured using type K thermocouple into the predeened layers of Cr (5 nm) and Au (50 nm) into a thickness suitable for use as sensing/heating element. The thermal deposited devices were immersed into dimethyl sulfoxide (DMSO) solution to complete lift off process. Silver paste was smeared onto interconnects and connected with extended thin copper wire (13 µm). Parylene layer (500 nm) was deposited on top of the device to serve as a passivation layer using CVD.

Ex Vivo Porcine Liver Heating Studies: Similar to the experiment for extraction of thermal properties of the porcine liver, the porcine liver was first frozen in the fridge (0 °C) warmed with deionized water (25 °C) for 1 h. The device was then laminated on the organ with external connection copper wires (14 µm). The device was connected to power supply sourcemeter (Keithley 2636) through external connection wire. The power inputs were from 0 to 400 mW. During the ablation, the thermography was captured using infrared camera (FLIR, FLIR ONE Pro).

Integration with Robotic Palm as HMI: The device, which served as thermal sensor, was laminated on the finger of the robotic palm (ROBOTIQ, 3-Finger Adaptive Robotic Gripper). The robotic palm was programmed to grip a bottle of water with temperature ranging from 30 to 60 °C. The resistances of the device and the water temperature were recorded by sourcemeter (Keithley 2636) and infrared camera (FLIR, FLIR ONE Pro), respectively. In contrast, the device, which served as thermal actuator, was laminated on lab glove (LabSource, SafePoint Disposable Nitrile Exam Grade Gloves Blue). The thermal actuator was applied with electrical input from sourcemeter and heated up with corresponding temperature. The heating temperature of the thermal actuator was measured by infrared camera. A LabView program was written to transform the temperature of the object, which was measured by the thermal sensor, into the heating temperature of device laminated on the lab glove. Consequently, the robotic palm was programmed to grasp the bottle of water with designated temperature, a corresponding heating temperature was triggered in the device on the glove. The whole process was videoed in infrared camera (FLIR, FLIR ONE Pro).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

conformal heaters, temperature sensors, thermal feedback human–machine interface

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