Ultrahigh Sensitive Au-Doped Silicon Nanomembrane Based Wearable Sensor Arrays for Continuous Skin Temperature Monitoring with High Precision

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Monitoring the body temperature with high accuracy provides a fast, facile, yet powerful route about the human body in a wide range of health information standards. Here, the first ever ultrasensitive and stretchable gold-doped silicon nanomembrane (Au-doped SiNM) epidermal temperature sensor array is introduced. The ultrasensitivity is achieved by shifting freeze-out region to intrinsic region in carrier density and modulation of fermi energy level of p-type SiNM through the development of a novel gold-doping strategy. The Au-doped SiNM is readily transferred onto an ultrathin polymer layer with a well-designed serpentine mesh structure, capable of being utilized as an epidermal temperature sensor array. Measurements in vivo and in vitro show temperature coefficient of resistance as high as $-37270.72 \text{ ppm} / \degree C$, 22 times higher than existing metal-based temperature sensors with similar structures, and one of the highest thermal sensitivity among the inorganic material based temperature sensors. Applications in the continuous monitoring of body temperature and respiration rate during exercising are demonstrated with a successful capture of information. This work lays a foundation for monitoring body temperature, potentially useful for precision diagnosis (e.g., continuous monitoring body temperature in coronavirus disease 2019 cases) and management of disease relevance to body temperature in healthcare.

1. Introduction

Currently, technologies for body temperature sensing are developed for medical diagnosis, wound healing, monitoring skin hydration and blood flow. There has been a wide range of research on monitoring the body temperature with various methods, but a ultrahigh precision and continuous monitoring is not available for monitoring high-risk individuals, such as the viral infections, the children, and the elderly. For example, the current coronavirus disease 2019 (COVID-19) pandemic shows the importance of tracking the risk factors of the viral infections by monitoring body temperature. Conventional indirect temperature sensing using infrared (IR) camera is the most widely used method for temperature measurement. IR camera can measure the temperature precisely, but it can be heavily affected by the movement of the...
target area and the conditions of medium between IR camera and target sensing area. By contrast, the development of direct sensing approaches could minimize these issues and improve the measurement accuracy.[7,18] The epidermal temperature sensor is an excellent candidate to overcome the drawbacks of the conventional temperature sensors through a direct attachment on the skin surface because of the skin like physical properties such as stretchability, low Young’s modulus, and permeability.[2,8,12–16,19–23]

Compared to the organic materials, silicon, which is a classical representative inorganic material, shows high reliability under a quite broad range of working conditions due to its oxidation resistive property and also can sustain high temperature processing, such as doping.[15,23–31] Silicon-based temperature sensor provides relatively high sensitivity associated with temperature coefficient of resistance (TCR). Also, fast response time of silicon-based sensor compare to phase change materials is one of the marvelous advantages.[15] The properties of silicon, such as electrical conductivity and piezoresistive effect, can be modulated by controlling the dopants and doping concentrations.[32–34] Gold, which functions as deep impurity, can adjust fermi energy level of silicon and thus is expected to significantly improve thermal sensitivity.[35–41] However, doping the gold into silicon nanomembrane (SiNM) and the subsequent transfer to flexible substrate is extremely challenging. Here, we introduce a thin, ultrahigh sensitivity Au-doped SiNM temperature sensor array that enables the monitoring of human body temperature with a super high precision based on the fast response time and making a conformal contact to the skin for continuous monitoring. By controlling the gold doping concentration in SiNM, fermi energy level shifts and activation energy increases, which improves the sensitivity significantly. Transferring the ultrathin layer of Au-doped SiNM to the polyimide substrate and patterning the whole device including interconnections into mesh with serpentine structure can minimize the strain applied to the active arrays. All materials composing the Au-doped SiNM temperature sensor are representative biocompatible materials[23,25–27] to have high potential to be applied as biomedical electronics. We demonstrate the technologies we developed for the most precise body temperature monitoring devices and show the examples of their capabilities continuous monitoring of body temperature.

2. Results

Generally, there are two types of diffusers for silicon: fast diffusers such as Au, Cu, H, O, and slow diffusers such as group III and group V elements.[32,34,44] Deep-impurities (e.g., of gold) occur compensation by ionization in p- or n-type doped silicon. Deep impurities increase the resistance of silicon, getting closer to the intrinsic region, and having the maximum resistance at the point of impurity concentration compensates with the acceptor (or donor) concentration. If more deep impurities are doped, the ionized donor (or acceptor) changes the p- (or n-) type silicon into n- (or p-) type silicon inducing the resistance decrease.[13] Gold atoms can be rapidly substitutional-interstitial diffused in silicon with Frank–Turnbull mechanism and kick-out mechanism over 1000 °C by penetrating into silicon atoms and moving from interstitial site to other sites and, thus, are employed to dope silicon.[45,46] Figure 1a shows schematic illustration and scanning electron microscopy (SEM) images of SiNM before and after gold doping. When applied temperature increases, due to the formation of electron–hole pairs, free-electron concentration increases, which lowers the resistivity of Au-doped SiNM. For the saturation region of semiconductor such as silicon, temperature mainly affects the mobility and electron density does not change critically. This indicates that high sensitivity cannot be achieved in saturation region. Therefore, for the high temperature sensitive semiconductor, temperature sensing range should be in freeze-out region or intrinsic region.[47] Since the intrinsic region is ultrahigh temperature, the temperature sensor must operate at freeze-out region, considering the temperature range that we need to measure. Energy levels and properties of semiconductors are changed with the introduction of impurities.[37,40,41] Thus, deep-impurity in silicon causes the freeze-out region to move toward the intrinsic region, and proper concentration control allows the silicon to have high temperature sensitivity. Gold acts as deep impurity in silicon, ionizing and compensating with acceptor (or donor). As a result the fermi energy level of p-type silicon shifts to the intrinsic level, simultaneously shifting the freeze-out region to the intrinsic region. Therefore, the Au-doped SiNM operates at freeze-out region rather than saturation region for the target temperature sensing range, as highlighted in orange in Figure 1b. The slope of the resistivity–temperature curve is TCR, which is proportional to activation energy.

In theory, the TCR of p-type silicon is $\text{TCR} = \frac{dR/R}{dT} = -\frac{E_A}{T^2}$ [39]

where $R = C e^{E_A/kT}$, $C$ is a constant, $E_A$ is the activation energy, $k$ is Boltzmann’s constant, and $T$ is temperature. Figure 1c illustrates the schematics of energy level. Given the Fermi level energy $E_F$, $E_A = E_F - E_V$, where $E_V$ is the energy at the top edge of the valence band. When the p-type silicon is doped by gold, the Fermi level energy becomes $E_f = E_0 - kT \ln \left( \frac{N_S}{2(N_{Au} - N_i)} \right)$, where $E_0$ is the donor level energy of gold, $N_S$ is the concentration of acceptor (boron), and $N_{Au}$ is the concentration of gold.[40,41] Therefore, the TCR of gold-doped p-type silicon is

$$\text{TCR} = -\frac{E_0 - E_V - kT \ln \left( \frac{N_S}{2(N_{Au} - N_i)} \right)}{T^2} \quad (1)$$

where $E_0 - E_V = 0.35$ eV.[40] Figure 1d and Figure S1 (Supporting Information) show the concentration profile of gold atoms in diffusion depth direction of the stable Au–Si mixed system when the diffusion of gold atoms is completed. It shows the concentration is almost a constant at the middle plateau stage, suggesting nearly uniform distribution of the gold atoms in the silicon after the diffusion. The molecular dynamics (MD) simulation snapshots further confirm this uniform distribution. The concentration of gold in the silicon is taken at that the plateau stage $N_{Au}$. Similar results have also been obtained at different doping temperatures, as shown in Figure S2a of the Supporting Information. Furthermore, higher temperatures lead to lower gold concentrations of $N_{Au}$. The mean square displacement (MSD) of gold atoms diffusion is calculated to quantitatively characterize...
the diffusion coefficient $D$ of gold atoms in Figure S2b of the Supporting Information. A large diffusion coefficient $D$ is obtained at a higher doping temperature shown in Figure S2c of the Supporting Information, leading to a deeper diffusion of gold atoms into the silicon bulk and a lower $N_{Au}$. Figure S3 of the Supporting Information further shows the effect of initial thickness of gold film $t_{Au}$. The gold concentration $N_{Au}$ is almost the same for different gold thicknesses $t_{Au}$ and the maximum diffusion depth $H$ increases with the increasing of gold thickness $t_{Au}$ and temperature. Besides, because the MD simulation is an idealized situation, all the gold atoms can be diffused into the silicon before the saturation, which gives a larger gold doping concentration compared to the experiments. Figure 1e shows the theoretical calculations of $E_A$ and TCR of the Au-doped SiNM as a function of gold atoms concentration $N_{Au}$. Further, unlike most
inorganic materials and p-type or n-type silicon, at the target temperature sensing range, Au-doped SiNM has a negative TCR, which corresponds to a decrease of resistivity as the temperature increases.

Figure 2a illustrates the fabrication process of ultrathin, highly sensitive Au-doped SiNM temperature sensor. In brief, first, thin layer of gold is thermally evaporated and annealed in oxygen abundant environment for diffusion of gold atoms into SiNM. By controlling the deposition thickness of gold layer (10 nm) and annealing temperature (1000–1100 °C) precisely, proper concentration of gold ions can be doped into SiNM. Then the Au-doped SiNM (300 nm) is transferred onto the 1.5 μm polyimide (PI) layer, followed by the selective etching process of the transferred thin layer of Au-doped SiNM to form serpentine structure to form an array of 4 × 4 pixels. The window of resistance change with respect to the temperature change can be larger by patterning serpentine structure to the Au-doped SiNM, which leads to increase in the initial resistance value substantially. A layer of the 400 nm Cu is thermally evaporated to form the interconnects and patterned into serpentine structure. The additional PI layer for encapsulation layer is spin-coated and etched into serpentine structure using metal hard mask. A total thickness of ~3.5 μm of the device enables the conformal contact when attaching to the skin. Afterward, the water-soluble tape to pick up the device is attached on the mesh structured ultrathin, highly sensitive Au-doped SiNM temperature sensor array. After transferring the Au-doped SiNM temperature sensor array to water, soluble tape is dissolved by water and only the device is attached on the skin. Details of the fabrication process and the transferring process of the device are explained in the Experimental Section. Figure 2b shows the conformal contact of Au-doped SiNM temperature sensor array on the skin of forearm. The whole device has a serpentine mesh structure with isolated island to minimize the strain effect on sensing area. The sensing layer of the Au-doped SiNM temperature sensor array is sandwiched between the same thickness of PI and is positioned to the neutral mechanical plane of the device, which helps avoid the effect of bending strain on the active region. The active areas are completely isolated by the square shape islands while interconnects and device structures have mesh structures. To prove the functionality of array for the temperature monitoring with a good spatial resolution, temporal heat (1–5 s) with aluminum shadow masks that serve as local heat filters with six different open letter shapes (‘Y’, ‘O’, ‘N’, ‘S’, ‘E’, and ‘I’) is applied by illuminating the IR lamp onto the top surface of the temperature sensor array. Figure 2c shows the high spatial distribution of thermal mapping under the filtered heat and the color of top surface and height of bar of the pixel represent the temperature in color heat map. The heat mapping results which is transferred process of the device are explained in the Experimental Section. Figure 2d shows the high spatial distribution of thermal mapping under the filtered heat and the color of top surface and height of bar of the pixel represent the temperature in color heat map. The heat mapping results which is monitored by IR camera clearly corresponds to the data acquisition system (DAQ) result, which had been monitored by Au-doped SiNM temperature sensor array. The schematics of DAQ setup for partially heated sensor array shown in Figure S4 of the Supporting Information. The results demonstrate that the Au-doped SiNM temperature sensor array shows a high spatial resolution that well corresponds to the results using the high-performance IR camera.

Figure 3a shows the relative resistance changes with respect to the increase in temperature for various temperature sensors such as Au-doped SiNM temperature sensor, conventional epidermal gold temperature sensor, and boron-doped SiNM temperature sensor. Among them, the Au-doped SiNM temperature sensor shows the highest TCR, which is ~37270.72 ppm °C¹, while TCR of conventional epidermal gold temperature sensor and boron-doped SiNM temperature sensor exhibits 1691.07 and 1771.25 ppm °C¹, respectively. The sensitivity of Au-doped SiNM temperature sensor can be controlled by doping temperature and substrate doping concentration. Au-doped SiNM with higher doping temperature showed lower gold doping concentration and deeper doping depth (Figure S5, Supporting Information). Figure 3b and Figure S6 (Supporting Information) show that the magnitude of negative TCR increases when doping temperature decreases, in good agreement with simulation results in Figure 1d. For the ohmic contact, boron doping level of the substrate is required to be higher than 10¹⁸ cm⁻³ which is the minimum requirement of boron doping concentration for silicon degeneration. The lower substrate boron doping level shows the sensitivity of ~7936.59 ppm °C⁻¹ in Figure 3c. The TCRs and relative resistance changes with various conditions are summarized in Table 1. The results clearly demonstrate that, by placing the heated rod on conventional gold and Au-doped SiNM temperature sensor arrays with identical structures, Au-doped SiNM temperature sensor show much higher sensitivity associated ΔR/R₀ change compared to that of a conventional epidermal gold temperature sensor in Figure 3d. Therefore, by controlling the substrate doping concentration and doping temperature, the sensitivity of Au-doped SiNM temperature sensor can be significantly improved which is one of the most sensitive inorganic materials-based temperature sensor (Table S1, Supporting Information). Furthermore, as shown in Figure S7 of the Supporting Information, Au-doped SiNM temperature sensor shows relatively fast response time (<9 ms) compared to phase change materials.  

In Figure 3e and Figure S8 (Supporting Information), results of testing the cell-to-cell variation of Au-doped SiNM temperature sensor array clearly show that there is almost no cell-to-cell variation lower than 0.8%, which is neglectable. Figure 3f shows the reliability and stability of the device when monitoring the resistance change during cooling down and heating up the temperature. Further, the motion on human skin especially when at joint involves large stretching (Figure S9, Supporting Information). The finite element analysis (FEA) results shown in Figure 3g illustrate, under large uniaxial strains (30%) and biaxial strain (Figure S10, Supporting Information), the mechanical deformation in Au-doped SiNM temperature sensor array including both SiNM and PI is within the elastic deformation, far below the yield strain of materials. Figure 3h shows cyclic stretching test for 5000 cycles by applying 30% of tensile strain along the vertical direction of device and the change (ΔR/R₀ < 0.7%) in resistance is negligible. Experimental and simulation results represent that the Au-doped SiNM temperature sensor can measure the environmental temperature change with an excellent sensitivity subjected to mechanical loadings, thereby enabling ultrahigh sensitivity temperature monitoring.

Because of interference like sweat and movement, continuous monitoring of human body temperature and respiration
Figure 2. Fabrication of ultrathin, highly sensitive epidermal Au-doped SiNM temperature sensors and in vitro functional demonstration. a) Overview of the gold doping in silicon and fabrication process for Au-doped SiNM-based temperature sensor: 1) thermal evaporation of gold on p-type SOI wafer, 2) gold doping in silicon by annealing in tube furnace under oxygen abundant environment, 3) transfer printing the Au-doped SiNM using PDMS stamp on flexible substrate, 4) patterning the transferred Au-doped SiNM with serpentine design. Inset shows the magnified illustration of single cell, 5) metallization for interconnection, 6) PI encapsulation and patterning entire PI with mesh structure. Single cell of isolated Au-doped SiNM is represented in red box, 7) device delamination from PDMS substrate after application of a water-soluble tape, and 8) transfer the device on skin and dissolve the water-soluble tape. b) Optical image of the Au-doped SiNM temperature sensor device conformally attached on forearm (left), 4 × 4 temperature sensor array of patterned Au-doped SiNM on mesh structure with PI and metal interconnection (middle-left), optical image of serpentine structure of Au-doped SiNM transferred on square patterned PI, which isolates Au-doped SiNM temperature sensor from mechanical deformation (middle-right), magnified optical image of Au-doped SiNM surface. c) Color heat map of partially heated Au-doped SiNM temperature sensor array (top) and corresponding partially heated thermographic image measured by the conventional IR camera (bottom) (scale bar: 3 mm).
is very challenging. Ultrathin skin-like devices can be conformally and stably attached to target body parts by van der Waals force, including encapsulation layer that act as moisture barrier and electrical insulation. Serpentine mesh design with isolated island structure of device minimizes the physical effects of sweat and mechanical strain applied to sensing area. Au-doped SiNM temperature sensing devices, which are attached to the back and philtrum measure the human body temperature change and monitor the respiration by detecting temperature difference of inhale and exhale during cycling in Figure 4a. Figure S11 of the Supporting Information represents the camera image of cycling and DAQ setting schematic. Metal-based sensors (Au) with the same structure were used to compare temperature sensing

![Figure 3. Measurements and characterizations of Au-doped SiNM temperature sensor performance. a) Relative resistance responses to temperature (Au-doped SiNM; red, conventional epidermal gold temperature sensor; orange, boron doped Si; black dashed). b) Temperature responses to different gold-doping temperatures (1000 °C, red, 1050 °C, pink, 1100 °C; purple). c) Temperature responses to different substrate boron doping level with gold doping temperature of 1000 °C (boron doped 10¹⁹ cm⁻³; black dot, boron doped 10¹⁸ cm⁻³; blue, gold doped with 10¹⁹ cm⁻³ boron doped substrate; green, gold doped with 10¹⁹ cm⁻³ boron doped substrate; purple). d) Optical image of heated rod placed on the Au-doped SiNM temperature sensor array, scale bar: 5 mm (left). Measured relative resistance results of conventional epidermal gold temperature sensor (top) and Au-doped SiNM temperature sensor (bottom). e) Hysteresis test by heating and cooling down the temperature of Au-doped SiNM temperature sensor. f) Cell-to-cell variation result with inset showing the magnified scale of red box. g) FEA results with 30% horizontal (left) and vertical (right) uniaxial strain applied. h) Cyclic stretching test for stability of Au-doped SiNM temperature sensor array by applying 30% uniaxial strain.]

| Substrate type | Gold doping temperature | TCR at 35 °C [ppm °C⁻¹] | ΔR/R₀(25–45 °C) |
|----------------|-------------------------|--------------------------|-----------------|
| Gold (50 nm)   | –                       | 1691.07                  | 3.36            |
| Boron 10¹⁹ cm⁻³| –                       | 542.23                   | 1.11            |
| Boron 10¹⁸ cm⁻³| –                       | 1771.25                  | 3.61            |
| Boron 10¹⁹ cm⁻³| 1100 °C                 | −7652.53                 | 12.25           |
| Boron 10¹⁸ cm⁻³| 1100 °C                 | −7936.59                 | 15.87           |
| Boron 10¹⁹ cm⁻³| 1050 °C                 | −17 410.71               | 33.16           |
| Boron 10¹⁸ cm⁻³| 1000 °C                 | −37 270.72               | 63.79           |
properties of Au-doped SiNM temperature sensors and conventional gold epidermal temperature sensor. As shown in Figure 4b, when the body temperature rises from ≈32.3 to 34.1 °C during exercise, the resistance of our Au-doped SiNM temperature sensor represents remarkable change, with rate of ≈4.2%, while the resistance of conventional epidermal gold temperature sensor exhibits small change, with a rate of 0.23%.

Figure 4. Evaluations of continuous body temperature and respiration monitoring by Au-doped SiNM temperature sensor. a) Ultrathin Au-doped SiNM temperature sensors attached conformally on various positions of body; on the back for body temperature monitoring (red box) and on philtrum for respiration monitoring (blue box). b) Real-time monitoring of body temperature during cycling. Subject: 26-year-old male, 79 kg, 179 cm, nonprofessional volunteer (body temperature measured by various methods: Au-doped SiNM temperature sensor; red, conventional gold temperature sensor; black, digital thermometer; green dot). c) Continuous monitoring of respiration by Au-doped SiNM temperature sensor transferred on philtrum near nasal cavity. Subject: 26-year-old male, 62 kg, 170 cm, nonprofessional volunteer (Au-doped SiNM temperature sensor; red, conventional epidermal gold temperature sensor; black, heart rate; blue). d,e) Magnified scale of respiration during rest (heart rate, 138 bpm) and cycling state (heart rate, 193 bpm) (Au-doped SiNM temperature sensor; red, conventional epidermal gold temperature sensor; black). f) IR camera images of nasal cavity temperature differences during exhale (left) and inhale (right).
Respiration measurement is more complicated and difficult than body temperature, due to small and rapid temperature changes. The temperature of the breath coming out of the nasal cavity changes while inhaling and exhaling (Figure S12, Supporting Information). We examined the capability of respiration monitoring with both Au-doped SiNM temperature sensor and conventional epidermal gold-based sensor as a point of comparison and checked the relationship with heart rate measured by smart watches, alternating resting and cycling 8 min each in Figure 4c. Figure 4d,e shows that conventional epidermal gold temperature sensor struggles with measuring temperature change of breathing during cycling. By contrast, the Au-doped SiNM temperature sensor clearly demonstrates respiration with precise change of resistance, which indicates faster respiration rate during cycling and slower respiration rate during resting. The monitored respiration results show identical inclination with respect to the heart rate change. Figure 4f shows IR images of inhale and exhale demonstrating that temperature change in philtrum during respiration is very small. These results demonstrate that our Au-doped SiNM temperature sensors are highly sensitive enough to detect even small and rapid changes and can accurately monitor temperature change by respiration, even if the sensors have the encapsulation layer that prevents sweat or moisture.

3. Conclusion

In this work, we have developed an ultrathin, highly sensitive Au-doped SiNM temperature sensor array with TCR of $-37270.72 \text{ ppm} \degree\text{C}^{-1}$ that vastly improves response sensitivity to temperature compared to silicon. We conducted gold doping under different conditions, varying the background boron doping concentration and doping temperature of gold doping. The result shows that the lower the background doping and the lower the doping temperature are, the higher the thermal sensitivity of the sensor would be. Au-doped SiNM temperature sensor arrays were transferred to flexible substrates after the high-temperature process, which allowed them to be made into very thin and stretchable mesh structures, including encapsulation layers. Therefore, the soft and flexible devices can be attached conformally on the body, enabling precise temperature change measurement and respiration monitoring without physical movements and moisture effects such as sweat. The Au-doped SiNM temperature sensor has a higher spatial resolution and accurate sensing capability compared to conventional epidermal gold sensors. We confirmed stability and accuracy of sensing performance by identifying high cell-to-cell uniformity and low hysteresis. Au-doped SiNM temperature sensor scales its use for medical diagnoses and treatments, including clinical research, medical procedures, and chronic temperature change monitoring in the body with capabilities for applying to local and large areas. In addition to temperature sensing, simulations in the properties of silicon through gold doping could be expanded to applications in high-performance Si-based electronics.

4. Experimental Section

Fabrication of Au-Doped SiNM Temperature Sensor: The first step of the fabrication process of Au-doped SiNM temperature sensor was thermal evaporation of gold on p-doped silicon. Gold doped into SiNM by annealing process in tube furnace with oxygen ambient condition for 2 h. Then Au-doped SiNM was transferred onto glass substrate spin-coated with sacrificial layer of PDMS (K1 Solution) and polyimide (poly(pyromellitic dianhydride-co,4,4'-oxydianiline) amic acid solution, Sigma-Aldrich). Dry-etching step with photolithography (S1805, Shipley) and reactive-ion etcher (Young Vacuum System) defined the serpentine design of Au-doped SiNM layer. Additional metallization with photolithography (AZ-5214, MicroChemicals) for contact and interconnects and polyimide spin-coating for encapsulation with photolithography completed the sensor fabrication process.

Characterization of Au-Doped SiNM: Field emission SEM and secondary ion-mass spectrometry (SIMS) measurements were conducted with SIMS-700IF from JEOI (Japan) and TOF-SIMS 5 from Ion-tof (Germany).

Molecular Dynamics (MD) Simulation: The MD simulations were conducted to model the diffusion of gold atoms in silicon using the Large-scale Atomic/Molecular Massively Parallel Simulator package. The interaction between all atoms was described using the angular-dependent interatomic potential. The initial system consisted of a gold layer on a silicon substrate. The time step was set at 0.1 fs. For the gold diffusion process, the MSD of gold atoms at time $t$ in $z$-direction can be calculated by

$$\text{MSD} = \frac{1}{N} \sum_{i=1}^{N} [z_i(t) - z_i(0)]^2,$$

where $N$ is the number of gold atoms, $z_i(0)$ is the initial position in $z$-direction of ith atom, and $z_i(t)$ is the position in $z$-direction of ith atom at time $t$. The diffusion coefficient of gold atoms in $z$-direction, $D$, can be calculated by the relation $\text{MSD} = 2Dt$.

Finite Element Analysis (FEA) Simulation: The FEA was conducted using the ABAQUS/Standard package. In the FEA model, the sensor structure was perfectly bonded to the elastomeric substrate to model the real situation of the sensor attached to the skin. The sensor was meshed by C3D10M element, and the substrate was meshed by C3D8R element. A biaxial strain (30%) or uniaxial strains (30%) to both vertical and horizontal directions was applied to the substrate for modeling mechanical stretching.

Array Sensor Performance Test: A fabricated 4 × 4 array of Au-doped SiNM temperature sensor was connected with flexible, thin connecting cable for external data collection. Aluminum shadow masks (Al, 300 nm) on glass with holes in the shape of certain letters ('I', 'Y', 'O', 'N', 'S', 'E', and 'T') were placed on top of an Au-doped SiNM sensor. Photolithography (AZ-5214, MicroChemicals) and wet etching (aluminum etchant type A, Sigma-Aldrich) were used to pattern the holes. Then, sensors under masks were partially heated, where the holes exist, with IR lamp. The resistance change of 4 × 4 temperature sensor arrays by applied heat was simultaneously monitored with the data acquisition system (NI PXIe, NATIONAL INSTRUMENTS CORP.).

Ethical Procedures for In Vivo: According to Article 13, Paragraph (1) of the Enforcement Regulations of the Bioethics and Safety Act of the Ministry of Health and Welfare, the authors confirmed that there is no need to obtain Institutional Review Board approval as volunteers have conducted research using wearable temperature sensors, simple contact measuring equipment without any physical modification nor invasive measurement on human shown in Figure 4. Also, the authors collected informed written consent from all volunteers.
Cycling Exercise Test 1
Body Temperature Measurement: A volunteer (26-year-old male, 79 kg, 179 cm) rode on an outdoor bicycle with the rear wheels fixed for use indoors. Au-doped SiNM temperature sensor was transferred on left and top side of subject’s back for sensing the body temperature change. After rest period (t = 0) for stability of temperature, the subject rode a cycle for 15 min. At t = 40 min, cycling exercise and the data were collected by digital multimeter (DMM 6500, KEITHLEY).

Cycling Exercise Test 2
Respiration Monitoring: A volunteer (26-year-old male, 62 kg, 170 cm) rode on an outdoor bicycle with the rear wheels fixed for use in indoor. Au-doped SiNM temperature sensor was transferred on subject’s philtrum for sensing the temperature change by nasal breathing. After rest period (t = 0) for stability of temperature, the subject rode a cycle for 8 min. At t = 14 min, a further 12 min of rest and 8 min of cycling were completed. At t = 40 min, cycling exercises and the data were collected by digital multimeter (DMM 6500, KEITHLEY).

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.

Data Availability Statement
Data available on request from the authors.

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