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Research paper

Moisture sensor based on heat transfer possessing insusceptibility to coating materials on skin

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ABSTRACT

This paper presents a thermal-based skin moisture sensor that is insusceptible to thin coating materials on skin. To realize this sensor, numerical simulations are performed to evaluate the influence of surface-coating materials, such as Vaseline moisturizer, on the heat transfer from a heat source in the sensor to the skin. The simulation results show that the influence of the thin Vaseline layer on the temperature change of the heat source is negligible, but the existence of air gaps between the sensor and the skin drastically interrupts the heat transfer. Considering the simulation results, the thermal-based skin moisture sensor is designed and fabricated with a microelectromechanical systems (MEMS) pressure sensor to avoid heat transfer interruption due to air gaps. The measurement results of water content in a water-absorbing polymer, covered with a 10-μm-thick polyethylene film, show that the moisture sensor can assess the water content of materials that are covered with a thin layer. Finally, we demonstrate the hydration measurement of skin with Vaseline coating. The measurement results confirm the potential of the moisture sensor to measure the water content of skin covered with moisturizing substances.

1. Introduction

To assess the effectiveness of moisturizers, such as creams, foundations, and ointments, it is necessary in cosmetic perspective to realize in vivo measurement of the water content of skins that are coated with moisturizers. The most popular methods to assess skin moisture are the electric impedance and capacitance measurement methods [1–5]. However, these methods have the drawback of being tremendously affected by the electric properties of moisturizer coatings composed of insulators or electrolytes, such as Vaseline [6–8].

For accurate skin moisture measurement, the thermal-based sensing method is one of best candidates because the thermal properties of skin are correlated with water content [9,10] and the heat transfer can reflect the thermal properties of the inner material (that is skin) under the thin surface-coating layer [11]. The thermal properties of the skin are also affected by the tissue blood flow [9,10]; this can be canceled by measures such as assessing the same skin spot before and after the moisturizer application. It has been reported that the self-heating operation of a thermistor has succeeded in measuring and distinguishing the thermal properties of bilayer skin phantoms [12]. Moreover, in 2010, we proposed a thermal-based MEMS moisture sensor integrating a pressure sensor in one chip, for estimating the local thermal contact condition [13]. Other studies have proposed a thermal sensor sheet, which can obtain a spatial mapping of the thermal characteristics of skin [14,15]. However, the influence of thin coating materials on heat transfer and the effect of air gaps formed by inadequate contact between the sensor device and skin should be evaluated for more accurate moisture measurement of surface-coated skin. In this study, we investigated the effects of thickness of surface-coating materials and air gaps on heat transfer through numerical simulations. Then, considering the simulation results, we designed and fabricated a thermal-based skin moisture sensor with a pressure-sensing component for monitoring the measurement condition. Finally, we demonstrated water content

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Abbreviations: MEMS, microelectromechanical systems; FEM, finite element method; PDMS, polydimethylsiloxane; PEN, polyethylene naphthalate; PE, polyethylene.

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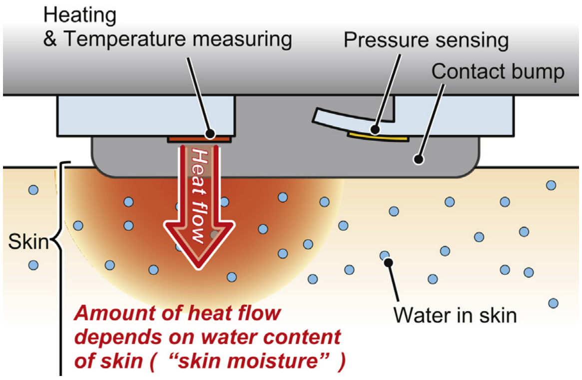

Fig. 1. Conceptual schematic of proposed moisture sensor functions.

measurement of skin coated with Vaseline ointment with the fabricated sensor. The results show that our moisture sensor has the ability to measure the hydration of coated human skin.

As shown in Fig. 1, the designed sensor has three functions: heating, temperature measurement, and pressure sensing. These three functional elements are embedded in a contact bump. The heating function applies a heat flux as a step function, and the applied heat is conducted through the contact bump to the skin. The heat conduction depends on the thermal properties of the skin, which are correlated with its water content; the more water the skin contains, the more heat is transferred from the heat source to the skin, resulting in a smaller temperature change in the heat source. Therefore, the water content of the skin can be estimated by monitoring the temperature of the heat source using the temperature measurement function. For precise thermal-based moisture measurements, it is essential to avoid the formation of air gaps between the skin and the surface of the contact bump, because the thermal properties of air drastically differ from that of solid or fluid materials such as skin and moisturizers. Therefore, the pressure-sensing function monitors the contact pressure during the measurement using a pressure sensor, which is integrated on the designed sensor. By applying an appropriate contact pressure, air gaps can be avoided because the surface texture of the skin follows that of the contact bump, which is made of a soft elastomer.

2. Heat transfer simulation

For confirming the validity of the thermal-based measurement, we performed finite element method (FEM) simulations in the time domain with the commercial software COMSOL Multiphysics, focusing on the effect of skin-coating materials. The simulation model was designed with rotational symmetry, as shown in Fig. 2(a). The model consists of skin coated with a material, a contact bump made from silicone elastomer (polydimethylsiloxane (PDMS)), an epoxy substrate coated with an SU-8 layer, and a heat source. The skin-coating material modeled was Vaseline, which is a typical moisturizer, and its thickness was set from 0 μm (no coating material) to 32 μm. As a reference, we also performed simulations with a model in which the Vaseline layer was replaced with air. The heat source is represented as a thin red line located at the interface between the SU-8 and PDMS layers. The heat source generates heat fluxes whose densities are set to be a step function signal changing from 0 W/m^2 to 3.1×10^4 W/m^2 in the time domain. The boundary conditions at the all edges of the computational domain were set as the open boundary condition. The thermal properties we used in this simulation are listed in Table 1. For estimating the thermal properties depending on the water content, we used the following equations [21]: $C_s = C_w\ \beta + C_t\ (1-\beta)$, $k_s = k_w{}^{\beta} k_t{}^{(1-\beta)}$, and $C = \rho\ c_p$, where C, k, β, ρ, and c_p are the volumetric heat capacity, thermal conductivity, water content ratio by volume, density, and specific isobaric heat capacity, respectively. The subscripts s, w, and t indicate skin, water, and tissue, respectively. In these calculations, we assumed that the normal skin water content ratio is 25 wt% [22].

Fig. 2(b) shows the profiles of the temperature change for skin (20 wt%) without a coating material. Fig. 2(b-i) shows the change in the temperature distribution for the proposed sensor and skin in contact with the sensor 3 s after the heat flux was generated. The temperature change became larger around the heater, which was located at the interface between the SU-8 and PDMS layers. The heat flux from the heater transferred toward the skin because both the PDMS and skin worked as heat conductors, similar to heat sinks for a heater. To clarify the profiles of the temperature changes in the PDMS and skin, Fig. 2(b-ii) plots the temperature changes at 0.5, 1.5, and 3 s. The plotted temperature changes were averaged over a circular area with a 164-μm radius that corresponded to the radius of the heater. The profiles show that the generated heat from the heater reached a depth of several hundred microns from the skin surface. Therefore, the sensor output affects not only the surface of the skin but also inside the skin. This result can help in realizing skin moisture sensors that are insusceptible to coatings on the skin.

Fig. 2(c) shows the time responses of average temperature of the heat source obtained from the simulation, with the skin water content ratio β changing from zero to one. Fig. 2(c-i), (c-ii), and (c-iii) shows the simulation results of the model without any coating material, with an 8-μm-thick Vaseline coating, and with an 8-μm-thick air layer, respectively. In all three figures, the temperatures quickly increase until 1 s regardless of whether a coating material is present or not. Moreover, the temperature variation at different water contents showed similar tendencies, that is, the temperature change increased as the water content in the skin decreased. In this study, we estimated the water content from the temperature change at 3 s with respect to the initial temperature of the heat source. Fig. 2(d) shows the simulated temperature change at 3 s, for different thicknesses of the skin-coating material. In the case of the model with no coating material, shown in Fig. 2(d-i), the sensor output linearly decreased as the skin water content increased. This tendency of linear decrease was consistent with the cases of the models with coating materials, as shown in Fig. 2(d-ii) and (d-iii). In particular, the differences between the sensor outputs for the models with no coating material and with less than 8-μm-thick Vaseline were small. On the other hand, in the case of the models with more than 8-μm-thick Vaseline or with air gaps, the differences between their sensor outputs and those of the model with no coating material were estimated to be quite large. These simulation results indicate that the thermal-based sensor has the potential to measure the moisture of skin with thin Vaseline coating. Moreover, the results show that the existence of air gaps between the contact bump and the skin highly influences the water content measurement.

3. Design and fabrication

The sensor design is shown in Fig. 3(a). The proposed moisture sensor mainly consists of a resistance-based thermal sensing component and a MEMS cantilever-based pressure-sensing component, both of which are embedded in an elastomer contact bump. The thermal sensing component simultaneously works as a heat source and a temperature sensor of the heat source. The elastomer, which is more than 100 μm in thickness, acts as an interface between the moisture sensor and the skin. During skin moisture measurement, the elastomer surface of the sensor presses on the skin as shown in the conceptual schematic in Fig. 1. The pressure-sensing component is based on the structure of a strain gauge formed on a cantilever. The cantilever deforms as the elastomer deforms