SKIN HEAT TRANSFER MANAGEMENT WITH CONTACT FORCE COMPENSATION FOR THERMAL STIMULATION APPLICATIONS

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Abstract: This paper presents a skin heat transfer device, where a force sensor is integrated to compensate the skin temperature change rate depending on contact force. Controlling temperature change rate is the key issue of skin heat transfer devices for thermal stimulation since human skin is highly sensitive to relative temperature change rather than absolute temperature. However, thermal resistance changed by contact force results in difficulties in controlling temperature change rate. The previous skin heat transfer device adjusting heating voltage by using temperature feedback for the compensation of thermal stimulation focused only on absolute temperature. The present skin heat transfer device, however, adjusts the heating voltage according to the contact force, thus achieving thermal stimulation with accurate control of skin temperature change rate. The present device with nickel micro-heater and piezoresistive force sensor has been designed, fabricated, and characterized. The experimental study shows that before and after adjusting the heating voltage according to the contact force, coefficient of variations of skin temperature change rate at varying contact force were 11.9% and 2.0%, respectively. Therefore we experimentally verify that the present device successfully compensates skin temperature change rate depending on the contact force. Due to its compensation ability of skin temperature change rate, the present device has high potentials for use in the thermal touch interfaces.

Keywords: Skin Temperature Change Rate, Contact Force Compensation, Heating Voltage Adjustment

INTRODUCTION

Recently, thermal feedback devices have been developed for human-computer interfaces and virtual reality applications. Human skin is highly sensitive to relative temperature change rather than absolute temperature [1] in thermal stimulation for thermal touch interfaces applications. Therefore, controlling skin temperature change rate is one of the key issues of skin heat transfer devices. However, conventional skin heat transfer devices [2, 3] have difficulties in controlling skin temperature change rate, since the thermal resistance is affected by the contact force between skin and contact area (Fig.1) which induce the change of skin temperature change rate. The previous skin heat transfer device [4] adjusting the heating voltage by using temperature feedback for the compensation of thermal stimulation focused only on absolute temperature. In this paper, we propose a novel skin heat transfer device where a piezoresistive force sensor is integrated to compensate the change of skin temperature change rate by adjusting heating voltage according to the contact force, thus achieving thermal stimulation with accurate control of skin temperature change rate.

DESIGN AND ANALYSIS

Figure 2 shows a schematic view of the present skin heat transfer device. The present device is composed of two components: a nickel heater and a silicon piezoresistive force sensor.

The structure and dimensions of the nickel heater are shown in Figure 3. We have determined dimensions of thickness, width, and length of the nickel heater as 0.3μm 150μm, and 5mm, respectively (Fig.3a), to heat the skin up to 40ºC in 20sec at the heating voltage of 20V and at the current of 0.1A.
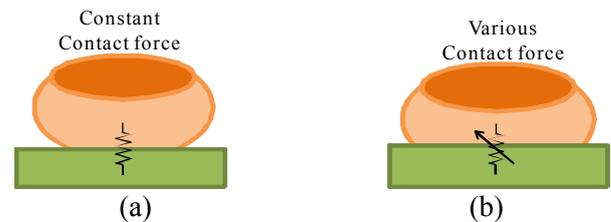

Figure 1. Thermal resistance depending on the contact force between finger and contact area: (a) constant contact force; (b) various contact force
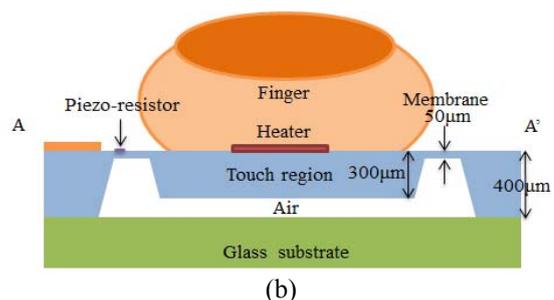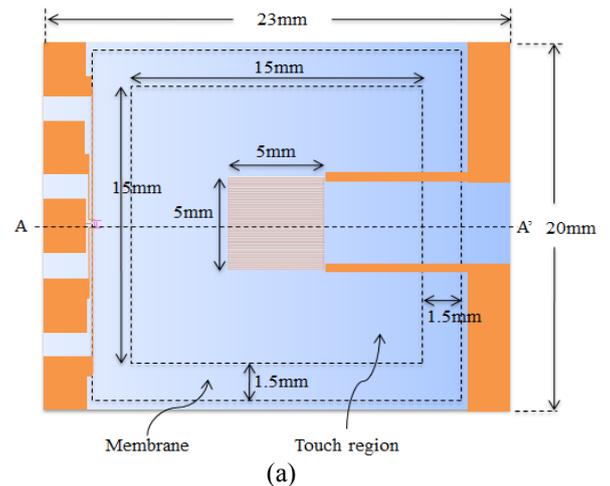

(a)

(b)

Figure 2. The skin heat transfer device: (a) top view; (b) cross-sectional view along A-A' of Figure 2(a).

Figure 4 shows the working principle of the piezoresistive force sensor which measures the contact force of the fingertip. Figure 4(a) shows the piezoresistors on the edge of membrane. When the force is applied to the touch region (Fig.4b), the membrane deflection detected by the piezoresistors occurs and finally induces the output voltage through the amplifier. In order to endure the force of 5N which is the maximum contact force of fingertip, the force sensor is designed with a 50μm-thickness and 1.5mm width square membrane with a concentric boss. Four p-type piezoresistors having width of 10μm and length of 200μm on the membrane are incorporated and connected in a Wheatstone bridge circuit for high sensitivity and temperature compensation (Fig.3b).

To adjust the heating voltage according to contact force for the compensation of skin temperature change rate, the following equation is used
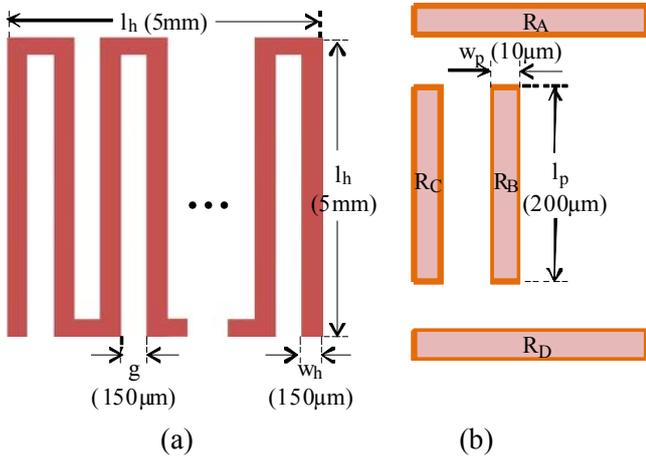
$$\frac{\Delta T}{\Delta t} = f(F) \tag{1}$$

(a)   (b)

Figure 3. Heater and piezo-resistor: (a) dimension of the metal heater; (b) dimension and arrangement of the boron-doped piezo-resistors.
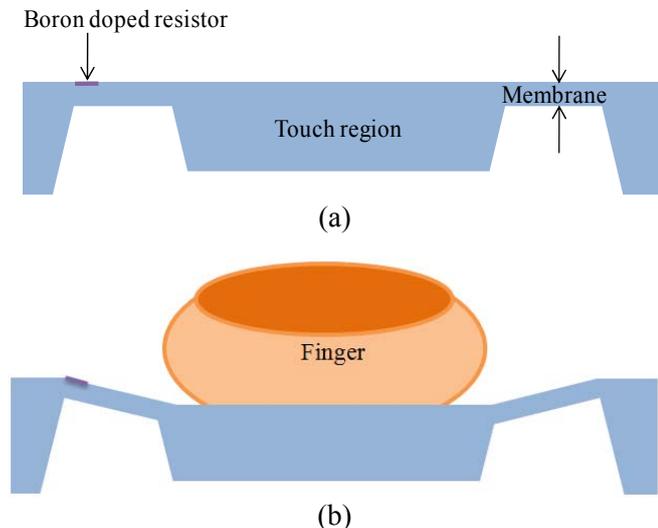

(a)

(b)

Figure 4. Contact force measurement based on membrane deflection detected by piezo-resistors: (a) structure of the force sensor; (b) force sensor with the finger contact.

where $\Delta T/\Delta t$ is the skin temperature change rate, f is the changed model of the skin temperature change rate according to the contact force, and F is the contact force. Skin temperature change rate is proportional to the heating power, thus heating voltage adjustment can be performed as following equation

$$V_{adjusted} = V \cdot \left(\frac{f(F_0)}{f(F)} \right)^{\frac{1}{2}} \tag{2}$$

where F_0 is the reference contact force V is the heating voltage, $V_{adjusted}$ is the heating voltage after adjustment. By using the adjusted voltage, $V_{adjusted}$ obtained from the Eq. (2), thermal stimulation with the consistent skin temperature change rate independent on contact force can be expected.

MICRO FABRICATION PROCESS

Figure 5 illustrates the fabrication process of the skin heat transfer device. The fabrication was started with 4', 400μm-thickness, and double polished N-type silicon wafer (Fig.5a). First, thermal wet oxidation with oxide target thickness of 1.5μm for insulation layer (Fig.5b) and patterning for the piezoresistors (Fig.5c) were performed. After boron doping (Fig.5d), Ti/Au of 200Å/2000Å and Cr/Ni of 300Å/3000Å were patterned on the silicon wafer for the electrode (Fig.5e) and the heater (Fig.5f), respectively. To form the membrane and the touch region, two backside bulk micromachining were processed using the 20% KOH solution in mass. First one is performed at the region of the membrane about 250μm of etching target (Fig.5g). Then second bulk micromachining with etching target of 100μm-thickness was followed (Fig.5h). Finally, the present device was fabricated after dicing the wafer to a unit device by using the Dicing saw. As shown in Figure 6, the skin heat transfer device was successfully manufactured. The measured dimensions of the present device compare to designed values are shown in Table. 1.
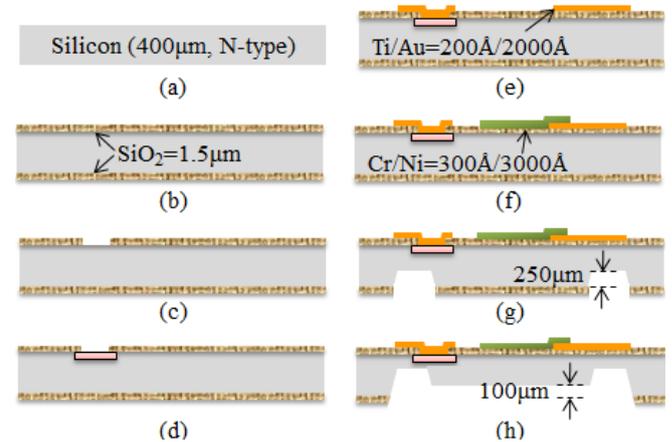

Figure 5. Fabrication process of the skin heat transfer device showing the cross-sectional view along A-A' of Figure 2(a).

Table 1. Designed and measured dimensions of the present thermal stimulator

Characteristics		Designed	Fabricated
Touch region	width & length, w_r	15mm	14.6±0.1mm
	Thickness, t	300 μm	279.3±0.9μm
Heater	Width & Length, l_h	5.0mm	5.10±0.05mm
	Pattern Width, w_h	150 μm	146.5±3.1μm
Force sensor	Membrane thickness, t_m	50 μm	66.3±1.6μm
	Membrane width, w_m	1.5mm	1.55±0.02mm
	Piezoresistor width, w_p	10 μm	14.6±1.7μm
	Piezoresistor length, l_p	200 μm	208.8±2.0μm

EXPERIMENTAL RESULTS

In the experiment, we first characterize the performance of the heater and the force sensor of the skin heat transfer device. Figure 7 shows the nickel heater performance measured at varying heating voltages. The nickel heater is capable to reach 40ºC in 15sec at the heating voltage of 20V.

Figure 8 shows the output voltage measured from the piezoresistive force sensor at varying contact force. The sensitivity and accuracy of the piezoresistive force sensor are measured as 1.7V/N and 0.05N, respectively, thus we confirm that the performance of the force sensor is able to measure of the fingertip contact force which range is 1~3N [5].

To verify the change of temperature change rate at the varying contact force, we measure the skin temperature using a thermocouple at the heater voltage of 20V at varying contact force. To avoid blood flow effect, fingertip is occluded. As shown in Figure 9, the contact forces of 1N, 2N, and 3N result in different temperature change rates of 0.415ºC/sec, 0.487ºC/sec, and 0.527ºC/sec, respectively, (Coefficient of variation (CV)=11.9%, Filled bars in Fig. 10).
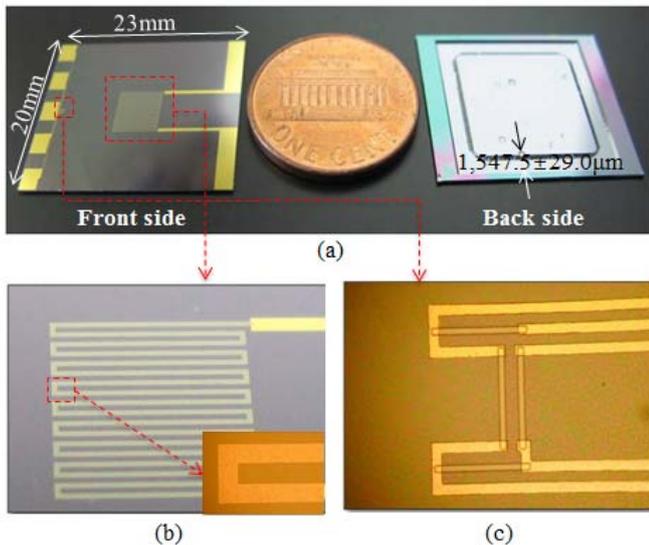

Figure 6. Fabricated device: (a) front-side and back-side view; (b) the enlarged view of the nickel heater; (c) the enlarged view of the piezoresistors.

From the result, skin temperature change rate at varying contact force shows quite high difference considering skin senses temperature change rate as small as 0.01 ºC/sec [6]. Therefore compensation of skin temperature change rate error due to contact force is required.

From the results, we experimentally confirm that changed model of skin temperature change rate in the range of 1~3N follows linear model. Therefore, using Eq. (1) and Eq. (2), adjusted voltage is

$$V_{adjusted} = V \cdot \left(\frac{a \cdot F_0 + b}{a \cdot F + b} \right)^{\frac{1}{2}} \qquad (3)$$

where a and b, which were obtained parameter from the experimental result of filled bars in figure 10, are 0.135 ºC/sec/N and 0.878 ºC/sec, respectively.

To compensate the skin temperature change rate changed by the contact force, based on Eq. (4), we have obtained the heating voltage of 20.0V, 18.5V, and 17.8V to compensate the skin temperature change rates at the contact forces of 1N, 2N, and 3N, respectively. At the adjusted heating voltage, the skin temperature change rates show consistent values of 0.415ºC/sec, 0.409ºC/sec, and 0.399ºC/sec, respectively (CV=2.0%, Blank bars in Fig. 10). We thereby experimentally verify that the present device successfully compensates the skin temperature change rate changed by the contact force.
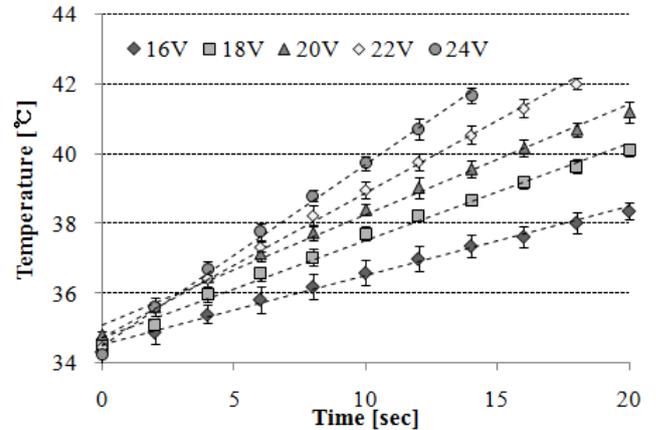

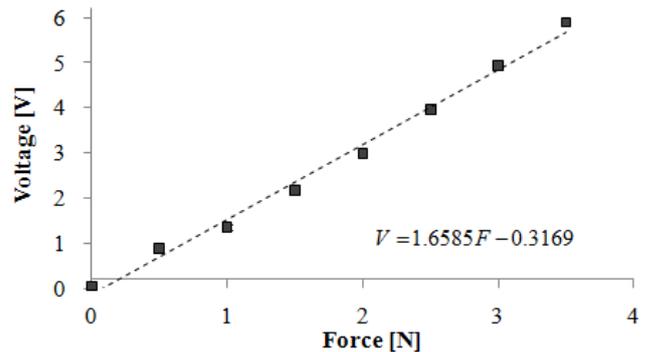Figure 7. Heating performance of the heater measured at varying heating voltage

Figure 8. Heating voltage measured from the piezoresistive force sensor at varying contact force.

CONCLUSION

We have designed, fabricated, and characterized the skin heat transfer device, where a piezoresistive force sensor is integrated to compensate the change of skin temperature change rate by adjusting heating voltage according to the contact force thus achieving thermal stimulation with accurate control of skin temperature change rate. Using the micro-fabrication technology, we successfully fabricated the skin heat transfer device with the piezoresistive force sensor. In the experimental study of the performance of the heater and the force sensor, the nickel heater with heating temperature of 40ºC in 20sec at the heating voltage of 20V and the force sensor with sensitivity of 1.7V/N and accuracy of 0.05N have been evaluated. In the experiment of measuring fingertip temperature at the heating voltage of 20V at varying contact force, the coefficient of variation of skin temperature change rate was 11.9%. We confirm that changed model of temperature change rate in the range of 1~3N shows the linear model and obtain the equation for voltage adjustment according to the contact force. At the adjusted heating voltage, the coefficient of variation of skin temperature change rate was 2.0%, thereby experimentally verifying that the present skin heat transfer device successfully compensates the skin temperature change rate changed by the contact force. The present device has potentials for use in the miniaturized thermal touch interfaces.
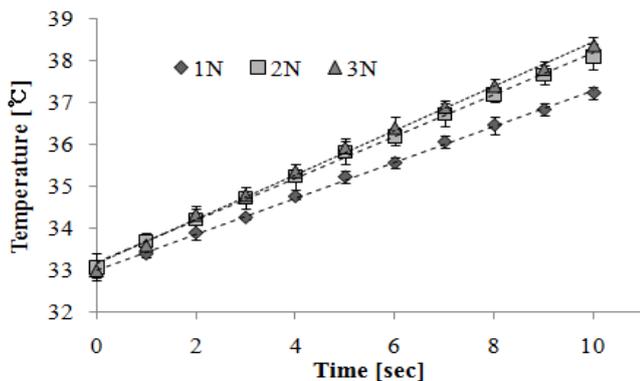

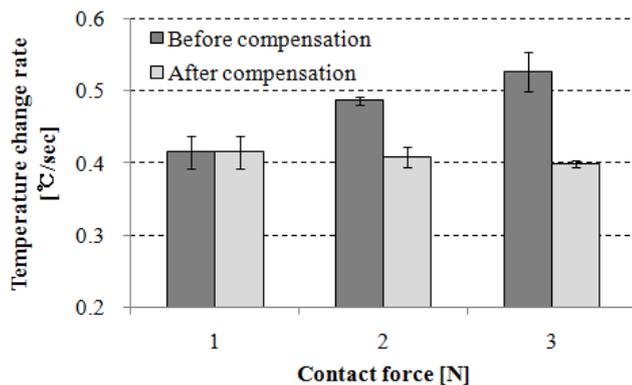*Figure 9. Skin temperature measured at varying contact force*

Figure 10. Comparison of skin temperature change rate changed by the contact force before and after adjusting heating voltage.

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