Development of temperature-control system for liquid droplet using surface Acoustic wave devices

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Abstract

In this paper, we present a liquid-droplet-heating system using a surface acoustic wave (SAW) device. When liquid is placed on a Rayleigh-SAW-propagating surface, a longitudinal wave is radiated into the liquid. If the SAW amplitude increases, the liquid shows nonlinear dynamics, such as vibrating, streaming, small droplet flying, and atomizing. This phenomenon is well known as SAW streaming. The liquid temperature is measured during the longitudinal wave radiation and found to increase. First, the mechanism of the liquid heating effect is discussed on the basis of experimental results. The surface electrical condition is changed to investigate the effect of dielectric heating. The obtained results indicate that the radiated longitudinal wave causes liquid heating and the dielectric heating effect does not. Second, the fundamental properties of the liquid temperature are measured by varying the applied voltage, duty factor, and liquid viscosity. The liquid temperature is found to be proportional to the duty factor and the square of the applied voltage. Therefore, the liquid temperature can be controlled by these applied signals. Also, by using highly viscous solutions, the liquid temperature is increased to more than 100 ˚C. Moreover, for chemical applications, the possibility of periodic temperature control is tested by varying the duty factor. The obtained results strongly suggest that an efficient thermal cycler is realized. A novel application of the SAW device is proposed on the basis of SAW streaming.

1. INTRODUCTION

Surface acoustic wave (SAW) devices are extensively used as analog electrical filters for mobile and wireless communications [1]. A Rayleigh wave is a true SAW, which has an elliptical displacement on the surface due to the combination of a displacement in the direction parallel to the SAW propagation and that normal to the SAW propagation surface. When liquid is loaded on the Rayleigh-SAW propagating surface, the Rayleigh-SAW becomes a leaky-SAW and a longitudinal wave is radiated into the liquid [2]. While this phenomenon is unfavorable for SAW device applications, such as filters, new applications have been created based on it. If the SAW amplitude increases, the liquid shows non-linear dynamics, such as vibrating, streaming, small droplet flying, and atomizing. This phenomenon is well known as SAW streaming [3, 4]. The theory for SAW streaming was derived from an acoustic streaming theory [4, 5]. The SAW streaming force is proportional to the squares of the SAW amplitude and frequency. As the SAW amplitude is directly proportional to the applied voltage [6, 7], the SAW streaming force can be controlled by an electrical signal. Therefore, a SAW streaming phenomenon can be classified according to the applied voltage [7]. The SAW streaming phenomenon has been applied for a micromanipulator [6, 8], a liquid pump [4], an atomizer [7, 9, 10], and a lab-on-a-chip [11, 12, 13, 14].

It is well known that the SAW-propagating surface is heated, when the SAW amplitude is increased. We investigated whether the atomization by SAW streaming corresponds to the boiling [15]. We compared the temperature between the cases with or without a liquid thin film on a SAW substrate. When the liquid thin film was placed onto the SAW propagating surface, the temperature became higher than that on the surface without a liquid thin film [15], and atomization was observed at temperatures below 90 ˚C. On the basis of the results, we concluded that the atomization does not correspond to the steam production and a temperature control system for microliquid droplets is realized using the SAW device.

To develop a liquid droplet heating system using the SAW device, it is necessary to clarify the mechanism of the heating effect. There are two possible heating mechanisms on the piezoelectric

substrates.　One is due to dielectric heating [16] and the other is due to SAW streaming.　First, the liquid heating mechanism is elucidated by the experiment.　The heating mechanism is discussed by monitoring the amplitude of output signals and liquid temperature under different surface electrical conditions.　Second, the application of the liquid temperature control system is discussed.　The relationship between the liquid temperature and the applied signal is investigated.　Differences between liquids, such as distilled water, electrolyte, and glycerol/water binary mixture, are measured to determine the effects of liquid properties.　Finally, periodic temperature control is performed for realistic application.

2. EXPERIMENTAL

A 128° rotated Y-cut X-propagating LiNbO$_3$ single crystal [17] was utilized as a SAW substrate in this study.　As the crystal has the large electromechanical coupling coefficient of 5.5%[18], it was chosen.　An interdigital transducer (IDT) with 32 finger pairs, apertures of 2 mm, and a center frequency of 48.6 MHz was designed and fabricated on 128YX-LiNbO$_3$.　The experimental setup was shown in Ref. [15].　An RF signal of 48.6 MHz was generated using a standard signal generator (Leader 3220), and a pulse wave was generated using a multifunction synthesizer (NF Electronic Instruments 1940).　The pulse repetition frequency was fixed at 1 kHz.　The duty factor of it was modified in the experiment.　Then these two signals were mixed and amplified using an RF power amplifier (R&K A1000-510).　The amplified pulse-modulated RF signal was fed to the IDT.　In the experiment, the amplitude of the input signal was varied.　The amplitude was measured using an oscilloscope (Agilent 54615B).　A thermocouple thermometer (Fluke 51K/J) and a noncontact infrared thermometer (Horiba IT-240S) were utilized for temperature measurements.　Measurements were performed at room temperature (around 23 ˚C).

3. MECHANISM OF LIQUID HEATING EFFECT

Distilled water was used as target sample.   The water thin film was formed on the SAW device and its temperature was measured as a function of the applied voltage in Ref. [15].   The results were compared with those in the case without water layer.   Figure 1(a) shows the SAW device with a filter paper, in which the water thin layer was kept.   Figure 1(b) shows the results in the case with and without the water thin film layer.   The applied voltage and the duty factor were 35 V_{P-P} and 50 %, respectively.   The temperature in the case with the water layer is about two times higher than that in the case without water.   In the measurements, the SAW was generated from one IDT, thus we were able to monitor the amplitude of the output signal from the other IDT.   When the water thin layer was not loaded on the SAW propagating surface, the output amplitude was proportional to the applied voltage.   The slope was about −10 dB.   This value agrees with the insertion loss of the SAW device used.   When the water layer was formed on the surface, however, the output voltage decreased and it was about −40 dB.   This indicates that the energy of the SAW is converted to that of the longitudinal wave.   The radiated longitudinal wave causes the vibration in the water thin film layer and then the temperature of water increases.

Thus, the radiated longitudinal wave increases the temperature.   Next, the effects of the electrical condition of the propagating surface were measured.   When the propagating surface was metallized and grounded to the earth, the static potential due to the piezoelectric effect became 0. By comparing the electrically free surface with the electrically shorted surface, the effect of dielectric heating was confirmed.   Figure 2(a) shows the SAW device for this purpose.   When a normal IDT was used for generating the SAW, the SAW propagated on both sides of the IDT.   The propagating surface on the left side was electrically free, while that on the right side was electrically shorted by gold and chromium evaporated films.   A water droplet of 10 µl was loaded on the both surfaces.   To prevent the droplet from moving, the applied voltage was fixed at 10 V_{P-P}.   The duty factor was 50 %.   The obtained results are connected by straight line in Fig. 2(b).   The temperature was measured at 10-second intervals for two minutes.   The voltage was applied for

one minute. The temperature of the free surface was slightly higher than that of the shorted surface. The main cause of this temperature difference has been considered to be the heat conductor of the used material, because the thermal conductivity of gold is larger than that of the LiNbO$_3$ crystal. On the bases of these results, the effect of the static potential was ignored. In other words, the mechanism of liquid heating was considered to be due to the radiated longitudinal wave.

4. FUNDAMENTAL PROPERTIES

A. Water droplet

For realization of a liquid-heating system, the fundamental properties of liquid droplets should be measured. First, a distilled water droplet was placed on the SAW-propagating surface and the temperature was measured. To prevent droplet moving, the SAW was generated from two IDTs. Figure 3 shows the illustration of the SAW device. An evaporated circular metal film (Au/Cr) of diameter 2 mm was centered between IDTs. The liquid was placed on the circular film. When the droplet of 10 μl was placed on the film, a hemispherical droplet was formed. The applied voltage was also below 20 V$_{P-P}$ to prevent small droplet generation, i. e. liquid pump [4, 7]. Figure 4(a) shows the measured results. The duty factor was fixed at 50%. The temperature was measured at 12-second intervals for two minutes. The voltage was applied for one minute. The measurements were performed for various applied voltages. Similar to the case with the water thin layer film, the rise time was fast, while the fall time was less than 30 seconds. Therefore, rapid heating and cooling are possible using the SAW device. Because the cooling was realized by cutting off the input signal, there was no need for any cooling system. The rise and fall times will be discussed later. The water temperature increased with increasing applied voltage. The relationships between the applied voltage and the temperature at one minute are summarized in Fig. 4(b). The solid line in the figure indicates the fitting curve. The temperature was proportional to the square of the applied voltage. The amplitude of SAW was proportional to the applied voltage

[6, 7], so thus the temperature was proportional to the square of the amplitude. Also, as a SAW streaming force is proportional to the square of the amplitude [4], temperature is proportional to the SAW streaming force. Similar measurements were performed by varying the duty factor at the fixed applied voltage of 15 V_{P-P}. The temperature at one minute is shown in Fig. 5. The results were approximately expressed by a linear equation. In other words, the temperature was proportional to the duty factor. The correlation factor, R, was 0.997. Because an increase in duty factor indicates an increase in SAW exciting time, the obtained results are reasonable. Therefore, the liquid temperature can be controlled by both the applied voltage and duty factor. The temperature dependence of the water droplet volume was also measured. The volume was varied from 2 to 10 μl. Although the temperature of a small droplet was high, the maximum difference was about 3 °C. Therefore, we have concluded that the droplet temperature depends on the applied voltage rather than on its volume.

B. Droplets of Electrolyte and Glycerol/Water Binary Mixture

Electrolyte droplets, which were potassium chloride aqueous solution droplets, were placed on the circular film. Their conductivity was changed from 0 to 0.5 S/m and their volume was 10 μl. The experimental method was the same as that in Fig. 4. The results for different conductivities were in agreement with the result for in water. Therefore, we concluded that the differences in conductivity do not affect the temperature.

A glycerol/water binary mixture was selected as the liquid having physical properties different from those of water. A droplet of 10 μl of this mixture was placed on the surface. The applied voltage and the duty factor were fixed at 15 V_{P-P} and 50 %, respectively. Figure 6 shows the experimental results with the glycerol/water binary mixture concentration. The voltage was applied for one minute. The rise time of a droplet of low concentration was approximately equal to that of the water droplet. The rise time, however, increased with increasing concentration. When the concentration was above 40 wt.%, the droplet temperature was higher than that of the water droplet (see Fig. 6(b)). This can be explained in terms of the viscosity of the glycerol/water

binary mixture, which is listed in Table I. The viscosity rapidly increased from 40 wt.%. As the longitudinal wave was attenuated by viscous damping, a close connection between the viscosity and the temperature was observed. In other words, the temperature increase resulted from the heat loss of the longitudinal wave. It is difficult for the streaming phenomenon to arise in high-viscosity liquids. Therefore, when such liquids are placed on a surface, high-voltage signals can be applied to the IDT to realize high-temperature heating.

C. High-Temperature Application

For a water droplet, the maximum voltage that can be applied is 20 V_{P-P}. Because of this, it is impossible to realize a temperature higher than 50 ˚C. In this section, an 80 wt.% glycerol/water binary mixture was selected and measured. Due to the high viscosity, SAW streaming was not induced, thus the high-voltage signal was able to be applied to the IDT. Therefore, it is possible to heat up to a temperature higher than 50 ˚C. A 10 μl droplet was placed on the circular film. The applied voltage was varied and the duty factor was fixed at 50 %. The results are shown in Fig. 7. A high-temperature liquid heating was achieved with the glycerol/water binary mixture. The droplet was heated at 90 ˚C at 30 V_{P-P}. The rise time increased with increasing applied voltage. After the applied signal was cut off, the temperature spontaneously returned to room temperature due to heat radiation. As the temperature at one minute was proportional to the square of the applied voltage, such as that of the water droplet, it was easy to predict that high-temperature heating was realized by varying the duty factor. The duty factor was varied from 10 % to 80 % at intervals of 20 seconds. The results are shown in Fig. 8. The temperature increased in proportion to the duty factor and square of the applied voltage. The results agree with the previous relationships shown in Figs. 4(b) and 5. The highest temperature of 120 ˚C was achieved at the applied voltage of 30 V_{P-P} and the duty factor of 80 %. Therefore, the results suggest that the high-temperature liquid heating application is possible using viscous solutions. After the measurements, the SAW device showed no signs of damage.

D. Temperature Stability

   Temperature stability, particularly keeping temperature a constant value, is important for real applications of the SAW liquid heater, such as that in a chemical reactor.   The human body temperature of about 37 ˚C was selected.   A droplet from an 80 wt.% glycerol/water binary mixture was used.   The applied voltage and duty factor were fixed at 14.9 V_{P-P} and 50 %, respectively.   These values were determined based on the results in Fig. 8.   The obtained results are shown in Fig. 9.   The liquid temperature was maintained at 37 ˚C.   As the RF signal from the signal generator was modified with the 1 kHz pulse signal at the duty factor of 50%, the SAW was generated at intervals of 0.5 ms.   Because of this, the droplet temperature was maintained at 37 ˚C. We varied the pulse frequency and obtained similar results when the frequency was higher than 1 Hz.   Therefore, the liquid droplet temperature can be maintained constant under a certain input signal.

5. APPLICATION OF PERIODIC TEMPERATURE CONTROL SYSTEM

   The realization of periodic temperature control is also important for application of the SAW device in a liquid droplet temperature control system.   For the first example of such an application, the target temperatures of 37 ˚C and room temperature were selected.   The SAW was generated at 2-minute intervals.   The applied voltage and duty factor were fixed at 14.9 V_{P-P} and 50 %, respectively.   The experimental results are shown in Fig. 10.   From this figure, we found that the periodic temperature control is realized.   Here, rise and fall time constants are defined when the temperatures increase to T_{rise} and decrease to T_{fall}, respectively.   We defined T_{rise} and T_{fall} as follows.

$$T_{rise} = 0.632 \times (37 - T_{room}) + T_{room} \qquad (1a)$$

$$T_{fall} = 37 - 0.632 \times (37 - T_{room}). \qquad (1b)$$

Here, T_{room} is room temperature and 0.632 equals to 1-1/e.   From the figure, the rise and fall time constants are 7 and 8 seconds, respectively.   This rise time constant agrees with that in Fig. 8.

These results indicate that rapid temperature control is possible using the SAW device.

Figure 10 shows that the SAW device can be applied in a thermal cycler. In this actual application, however, high-temperature control is required. Such an application has resulted in the development of polymerase chain reaction (PCR) arrays [20, 21]. In the PCR, temperature is periodically controlled, for example ca. 95 $^\circ$C $\rightarrow$ ca. 50 $^\circ$C $\rightarrow$ ca. 70 $^\circ$C $\rightarrow$ ca. 95 $^\circ$C. Such temperature control was attempted using the SAW device. The temperature can be controlled by the applied voltage and duty factor, whereas the duty factor was changed at the fixed applied voltage of 30 V_{P-P}. The duty factor and target temperature are shown in Table II. Figures 11 shows the time responses of twelve cycles of periodic temperature control and the magnification between 450 s and 550 s, respectively. The expected temperature control was achieved by varying the duty factor, indicating that the SAW device can be applied in a PCR thermocycler.

6. CONCLUSIONS

Liquids can be heated using the Rayleigh-SAW device. The heating mechanism is revealed by experiment. The results of the observation of the output signal and the comparison of the surface electrical properties indicate that liquids can be heated by a radiated longitudinal wave. The relationships between the liquid temperature and the applied signals are determined. The liquid temperature can be controlled by the applied voltage and duty factor. The temperature is proportional to the duty factor and the square of the applied voltage. As the longitudinal wave is attenuated by viscosity, the liquid temperature increases with increasing liquid viscosity. A high-viscosity liquid can be heated to more than 100 $^\circ$C. Moreover, the liquid temperature is maintained at a constant under a constant applied condition.

For practical applications, a thermal cycler is proposed. By varying the duty factor at a certain applied voltage, periodic temperature control is realized. In an IDT with an input impedance of 50Ω, the applied power is determined by the applied voltage. When it is 30 V_{P-P}, the power is 2.25 W. In this study, an 80 wt.% glycerol/water binary mixture is used as a sample liquid for

high-temperature applications. In a PCR application, however, a low-viscosity liquid is normally utilized. As low viscosity liquids, such as water, cannot be directly heated to more than 50 ˚C, an indirect heating method is required. For example, the sample liquid is involved in a micro-encapsulation and then that is heated in the high viscous solution.

As a temperature sensor can be fabricated on a SAW propagating surface, an integrated system of heaters and sensors is realized. As the Rayleigh-SAW device can be applied in a droplet manipulator, it is possible to integrate both droplet-moving and droplet-heating systems on the SAW device. Therefore, a multifunctional lab-on-a-chip is realized using the SAW device.

In this paper, only the liquid temperature is discussed. The behavior of the radiated longitudinal wave in the liquid has not been cleared. A theoretical consideration and simulation are required for clarifying the SAW streaming. For modeling, we have observed SAW streaming in liquids [22]. Also, effects of SAW streaming on biomolecules are subjects for future study.

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Figure captions

Figure 1.   SAW device with the filter paper (a) and comparison of temperature between cases with and without water thin film layer (b).   Water is maintained in the filter paper [15].

Figure 2. Measurements of the effects of surface electrical properties.   (a) Device configuration; a water droplets are placed on electrical free and shorted surfaces.   (b) Measured temperature.

Figure 3. SAW device pattern for liquid droplet heating.   The liquid droplet is placed on the circular gold film of 2 mm diameter.   The hemispherical droplet is formed, when a 10 µl liquid droplet is loaded on the circular film.   The circular film is centered between the IDTs. The SAWs are generated from both IDTs.

Figure 4. Experimental results for 10 µl water droplet.   The duty factor is fixed at 50 %.   The temperature is measured at 12-second intervals for two minutes.   The voltage is applied for one minute.   (a) Time responses and (b) temperature obtained one minute after the voltage is applied.

Figure 5. Experimental results for 10 µl water droplet.   The applied voltage is fixed at 15 V_{P-P} and the duty factor is varied.   Temperature obtained one minute after the voltage is applied.   R indicates the correlation coefficient.

Figure 6.   Experimental results for glycerol/water mixture solutions with different concentrations. The volume of the liquid droplet is 10 µl.   The applied voltage and duty factor are fixed at 15 V_{P-P} and 50 %, respectively.   (a) Time responses and (b) temperature obtained one minute after the voltage is applied.

Figure 7. Experimental results for 80 wt.% glycerol/water mixture.   The volume of the liquid

droplet is 10 μl.   The duty factor is fixed at 50 %.

Figure 8. Experimental results for 80 wt.% glycerol/water binary mixture.   The volume of the liquid droplet is 10 μl.   The applied voltage and duty factor are the parameter used.   The duty factor is varied from 10 % to 80 % at intervals of 20 seconds.

Figure 9. Experimental result of temperature stability.   The sample is an 80 wt.% glycerol/water binary mixture.   The volume of the liquid droplet is 10 μl.   The applied voltage and duty factor are fixed at 14.9 V_{P-P} and 50%, respectively.

Figure 10. Experimental result of temperature stability.   The sample is an 80 wt.% glycerol/water binary mixture.   The volume of the liquid droplet is 10 μl.   The applied voltage and duty factor are fixed at 14.9 V_{P-P} and 50%, respectively.

Figure 11.   Experimental results of periodic temperature control application.   The sample is an 80 wt.% glycerol/water binary mixture.   The volume of the liquid droplet is 10 μl.   The applied voltage is 30 V_{P-P}.   The duty factor is varied.   Time responses of twelve cycles of the periodic temperature control and magnification are shown.

Biography

Jun Kondoh received his BE degree in 1990, his MS degree in engineering in 1992 and his doctor of engineering degree in 1995, all from Shizuoka University.　From April 1993 to March 1997, he was a research fellow of the Japan Society for the Promotion of Science.　In 1996, he was a guest scientist at Karlsruhe Research Center, Germany.　In April 1997, he joined the Department of Systems Engineering, Shizuoka University as a research associate and was promoted to associate professor in 2003.　In 2006, he became an associate professor of the Graduate School of Science and Technology, Shizuoka University.　His current research interests include surface wave based sensors and actuators, such as SAW and surface plasmon.　He is a member of the Acoustic Society of Japan, Japan Society of Applied Physics, IEEJ, the Institute of Electronics, Information and Communication Engineers (IEICE), the Electrochemical Society of Japan, and IEEE.

Norifumi Shimizu received his B.E. and M.S. degrees from Shizuoka University in 2002 and 2005, respectively.　In 2005, he joined Epson Toyocom Co. Ltd.　His research during his master course was applications of the SAW device.

Yoshikazu Matsui graduated from Shizuoka Industrial College in 1968.　He became a technician at Shizuoka University in 1966.　He has been involved in the R&D of mechanical sensors, ultrasonic actuators, and surface plasmon sensors.　He is a member of the Society of Instrument and Control Engineers and the Acoustic Society of Japan.

Mitsunori Sugimoto received his B.E. degree in 1971 from Shizuoka University, and M.S. and Dr. Eng. degrees in 1974 and in 1977, respectively, from Osaka University.　From April to March 1978,

he was a teaching fellow of the Osaka Electro-Communication University, and in April 1978 he joined the Research Institute of Electronics as a research associate.   His current research interest is the measurement of the optical anisotropy by the use of surface plasmon waves.

Showko Shiokawa received her B.E. degree in 1965 from Tohoku University, her M.S. degree in 1968 from the University of Electro-Communications and her Dr. Eng. degree in 1971 from Tokyo Institute of Technology.   In 1971, she became a research associate at Tokyo Institute of Technology.   In 1980-81, she was on leave at Bordeaux University, France, Institute of Neurophysiology.   In 1986, she became an associate professor in the Department of Opto-electric and Mechanical Engineering, Shizuoka University, and was promoted to professor in 1991.   In 2003, she retired, and is now the owner of SAW&SPR-Tech Corporation.   She has been engaged in research on the chattering of relays, holographic observation of surface acoustic waves, ultrasonic measurement of solvent biosensors and surface plasmons.   She is a member of the Acoustic Society of Japan, Japan Society of Applied Physics, the Institute of Electrical Engineers of Japan, and the Institute of Electronics, Information and Communication Engineers.

Tables

Table I. Density and viscosity of glycerol/water mixture at 20˚C [19]

Concentration (wt.%)	Density ($\times 10^3 Kg/m^3$)	Viscosity ($\times 10^{-3} Pa \cdot s$)
0	0.9982	1.002
10	1.0215	1.318
20	1.0459	1.817
40	1.0984	4.012
60	1.1530	12.31
80	1.2085	72.39
100	1.2611	1763

Table II. Target temperature and duty factor.

Temperature (°C)	Duty factor (%)
98	60
50	20
72-74	40
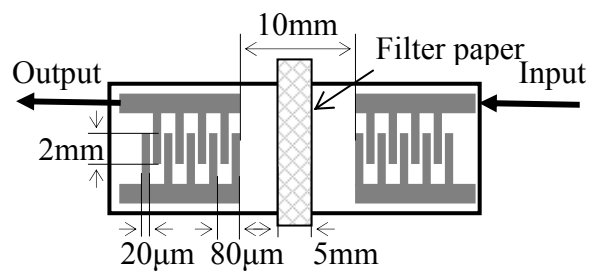
Figure 1(a).

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Figure 1(b).

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ca. 3mm   ca. 3mm

Water

Free surface
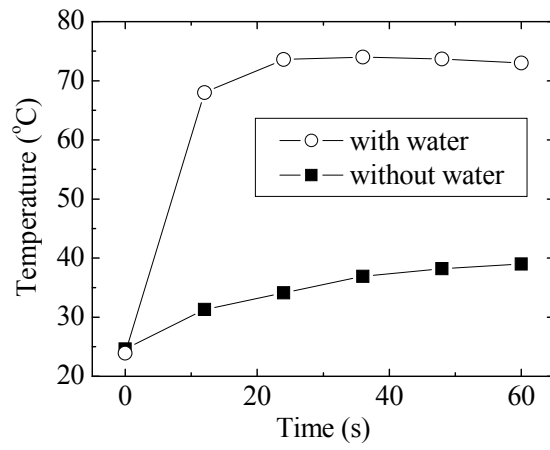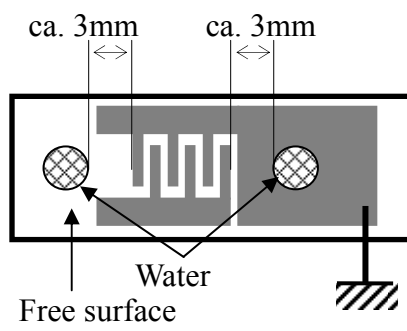
Figure 2(a).

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Figure 2(b).

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10mm

2mm

20μm 80μm

Diameter: 2mm
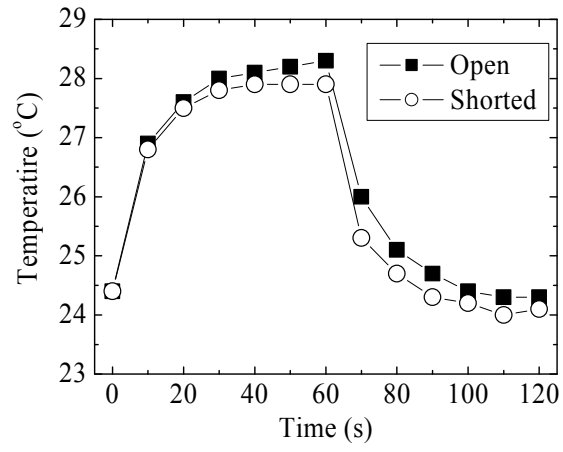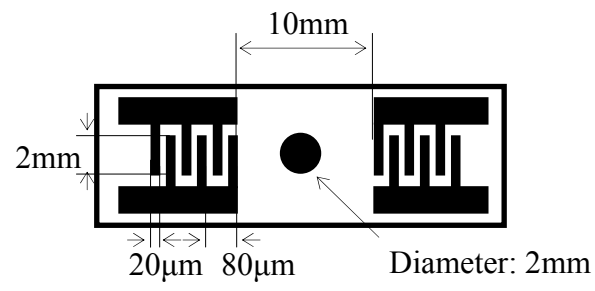
Figure 3.
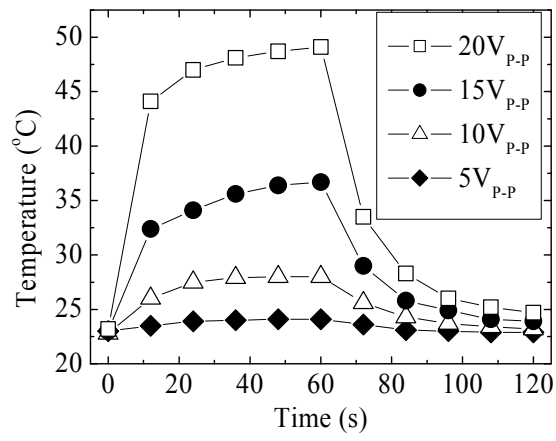
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Figure 4(a).

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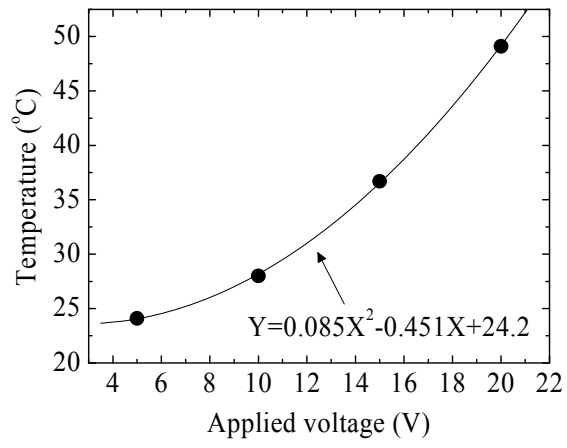
Figure 4(b).

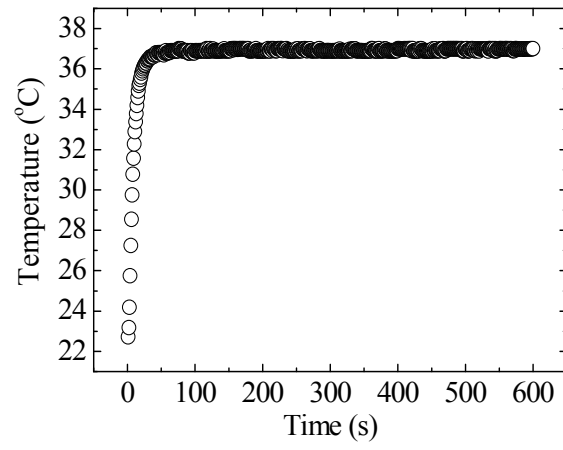Kondoh et al.

Y=24.0X+0.212
R^2=0.9970
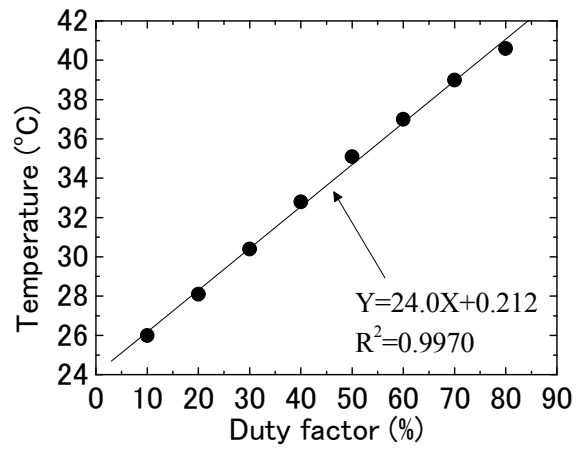
1/1

Figure 5.

Kondoh et al.
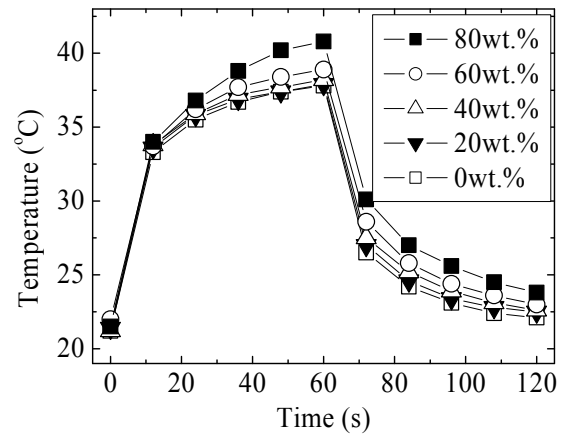
Figure 6(a).

Kondoh et al.
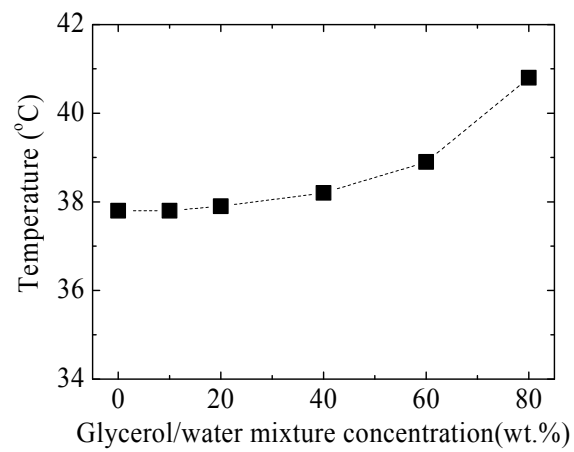
Figure 6(b).

Kondoh et al.
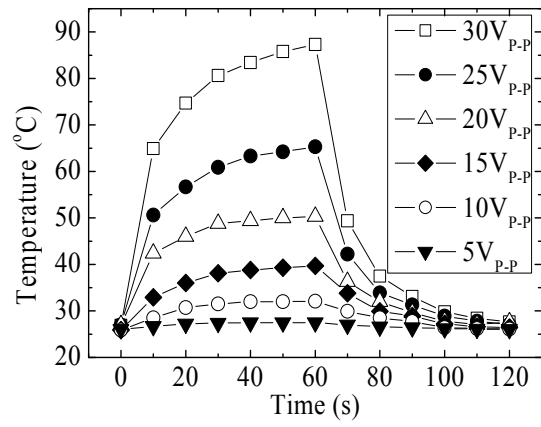
1/1

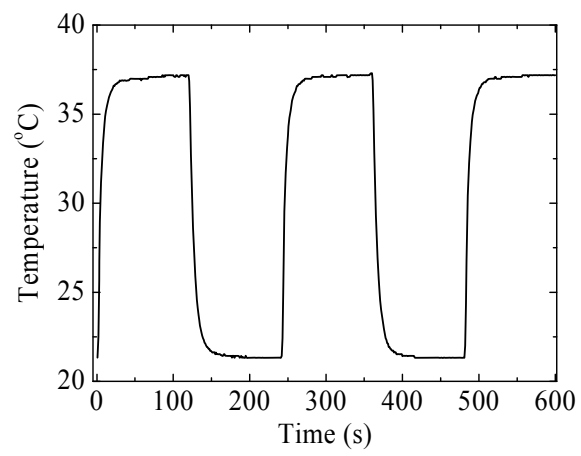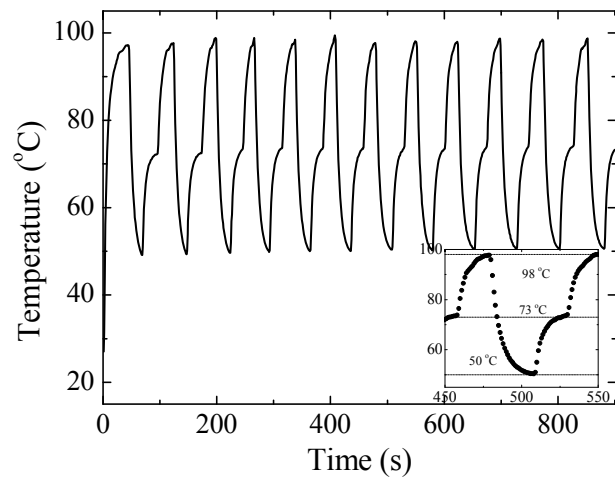Figure 7.

Kondoh et al.
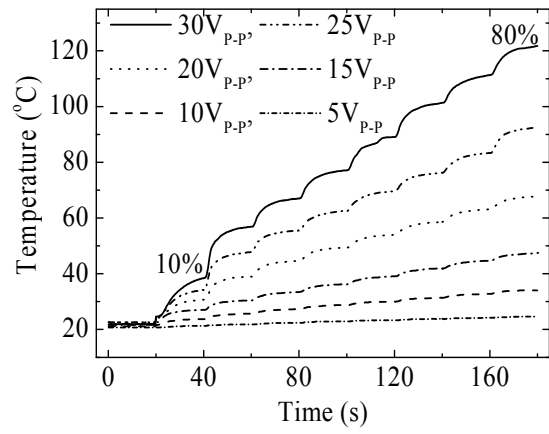
1/1

Figure 8.

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Figure 9.

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Figure 10.

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Figure 11.

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