Design and application of an LED using a liquid conductor for dissipating heat and conducting electricity

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Recently, the study of power consumption and heat dissipation has attracted considerable research interest due to the development of various electric products. In this research, the authors replaced the solid conducting wire with a microfluidic channel and an electrolyte to conduct electricity and dissipate heat in a light-emitting diode (LED). The optical power and temperature of the LED using three electrolytes including salt (NaCl), sodium bicarbonate, and citric acid were measured. The measured optical power was the highest when NaCl was used as the electrolyte. The temperatures of the LED and at the bottom of the microfluidic channel were much lower when a liquid conductor was used as compared to when a solid conducting wire was used. The optical power of the LED obtained using a solid conducting wire was higher than that obtained using a liquid conductor. The temperature decreased and optical power increased with increasing flow rate. They hypothesised that a liquid conductor with a lower electric resistance would improve the optical power of the LED.

1. Introduction: Energy supply and heat dissipation are important aspects of an integrated circuit design. In general, the solid metal conducting wires are used to conduct electric energy. Many methods to dissipate heat in integrated circuits have been proposed. Microfluidic devices are mainly used to dissipate heat in various electric products.

The effect of electrolyte concentration and pH value on microbial fuel cells has been previously studied [1]. Heat dissipation can be increased using a multi-microchannel copper heat sink [2, 3]. Moreover, the efficiency of heat dissipation could be increased and the internal temperature of a computer may be decreased using a multi-microsteam circulating system or a two-phase cooling system [4–6]. Chip or electric product temperatures may be decreased by employing a microfluidic channel design or a refrigerant [7–9]. Various designs for microchannels have been previously suggested, and an optimum design for heat dissipation was obtained [10]. There have been many investigations of heat dissipation in light-emitting diodes (LEDs). The LED chip temperature may be decreased by an integrated multi-fin heat sink design with a fan on metal core printed circuit board substrate [11]. The heat dissipation of an LED may be improved by using metal/carbon foam or cupric oxide and silicon-based resin [12, 13]. An aluminium nitride insulation plate substituted for the dielectric layer was used to achieve effective heat dissipation in a chip on board LED module [14]. The temperature of an LED may be rapidly decreased by using a dual synthetic jet actuator [15]. Two kinds of heat sinks have been suggested. One is a radicalised straight fin and another is a heat pipe. The heat dissipation effect may be enhanced by using a heat pipe with high thermal conductivity and the LED junction temperature may be efficiently reduced by raising the radiator height, increasing the number of fins and increasing the fin height [16]. However, these studies have focused on either heat dissipation or energy source and not on the combined effect of energy transfer and heat dissipation. The reliability and stability of an electric product may be decreased by as much as 10% when the temperature is increased by 2°C [17]. Therefore, it is imperative to suggest a method that can offer energy transfer and heat dissipation simultaneously. In this research, the solid conducting wire is replaced by a microfluidic channel and an electrolyte so that energy supply and heat dissipation can be achieved simultaneously.

2. Material and methods

2.1. Principle of operation: Since heat dissipation is a serious problem in the field of electronics, an effective solution is urgently required. A conducting wire that can dissipate heat and conduct electricity simultaneously is a possible solution. We propose a liquid conductor to dissipate heat and conduct electricity simultaneously, which would thereby effectively decrease the temperature of the electric product.

2.2. Chip design and fabrication: A microfluidic chip was designed (Fig. 1) and fabricated onto a poly methyl methacrylate (PMMA) substrate with flow channels 3 mm wide and 2.5 mm deep. A 1.5 mm deep indentation (length 16 mm and width 9 mm) was made to place the LED in the middle of the substrate. The size of the blank cover was $18 \times 50 \times 5\ mm^3$. It was considered that the light of LED could not be covered and the width of the blank cover (18 mm) was slightly larger than that of the bottom plate containing the channel (17 mm). A machined PMMA substrate and two independent blank PMMA covers were bonded together to form the device. The size of the entire chip was $50 \times 50 \times 10\ mm^3$. The LED (emitted colour: white, $V_f(v)$ (forward current $(I_F) = 350$ mA): 3.2–3.6, wavelength (nm): 5800–6300 K, luminous intensity ($I_F = 350$ mA): 120–130 lumen (LM), angle (2θ): 120, TY-HNW1–3, TaoYuan Electron Limited, Taiwan) was placed in the middle of the device. The conducting copper wire of the LED was connected to the liquid (or solid) conductor. Finally, the parts of liquid/solid conductor and the LED were integrated to form the overall chip (Fig. 2).

2.3. Sample preparation and experimental setup: Three electrolytes, salt (NaCl), sodium bicarbonate ($NaHCO_3$), and citric acid ($C_6H_8O_7$), were used as liquid conductors in this Letter. They were prepared with various saturation percentages from 20 to 100%. The flow rate was set using a syringe pump (EW-74901–60, Cole-Parmer, USA), and it ranged from 1.67×10^{-5} to 2.203 ml/min. A solid conducting nickel-plated steel wire was used, and its diameter is 1 mm. The power supply (LPS305, Motech, Taiwan) could produce an output voltage of ± 30 V. The chip, electrolyte, syringe pump, and power supply were integrated into the LED system. When the conducting wire of the LED was connected to the liquid (or solid) conductor and voltage was supplied, the temperature was measured using resistance temperature detectors (PT 100 series, OMEGA Engineering Inc., USA). The optical power and voltage of the LED were measured using an optical power meter (Gentec Electro-Optique Inc., Canada) and a voltage meter, respectively.

3. Results and discussion: The main goal of this Letter was to verify the feasibility of a liquid conductor. To this end, various electrolytes were tested and they were compared with the solid conducting wire. The compared items included the electric resistance, temperature, and optical power. Each set of experimental conditions was repeated at least five times, with average error <20%. The temperatures at nine locations (the centre and four corners of the bottom, four corners of the cover) were measured. The temperature variation at different locations was lower than 1.5°C when the temperature at the centre of the bottom was lower than 40 and 2°C if the temperature was higher than 40°C but lower than 50°C, so the temperature variation was not large at different locations. The temperature of the centre of the bottom was the highest, and it represented the temperature of the LED chip.

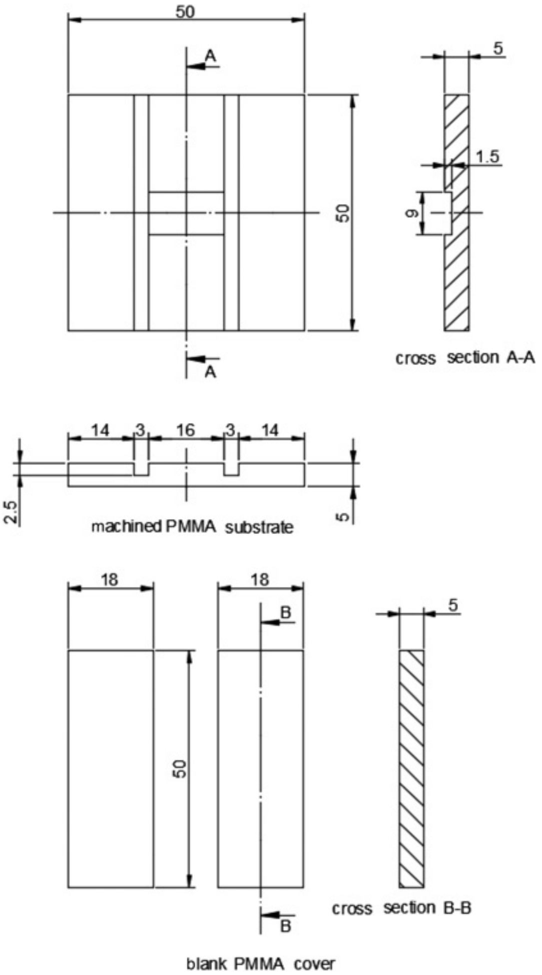

Fig. 1 *Schematic diagram of the microfluidic channel (unit: millimetres)*

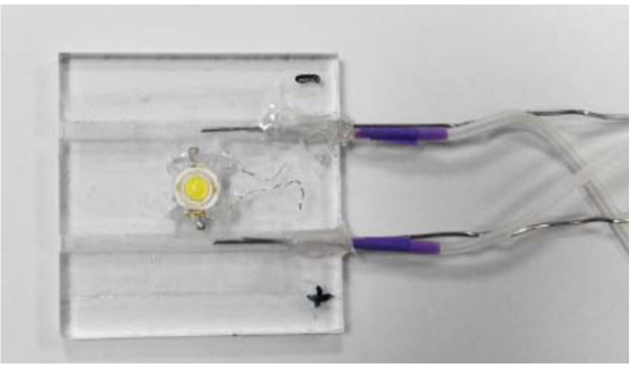

Fig. 2 *Photograph image of microfluidic channel and liquid/solid conductor*

3.1. Electric resistances of conductors: The electric resistances of the various conductors were measured, and the results are demonstrated in Table 1. The resistance of the nickel-plated steel wire was the lowest and that of $C_6H_8O_7$ electrolyte was the highest. The resistances and optical powers in the NaCl electrolyte conductors with various saturation percentages are compared and shown in Table 2 and Fig. 3. The resistance in the NaCl electrolyte conductor with 100% saturation was the lowest, and the optical power was the highest. Consequently, the electrolyte conductor with 100% saturation was selected.

3.2. Temperature and optical power using conductors with various electrolytes: First, a voltage of 3 V was supplied. The temperatures and optical powers of the LED systems were measured using different electrolytes and conducting wires. The room temperature as well as the temperature at the bottom of the microfluidic chip and the channel exit of the electrolyte in the microfluidic chip was measured. The optical power was measured at a distance of

Table 1 Electric resistances of various conducting materials

Conducting material	Electric resistance
NaCl	25.26 kΩ
$NaHCO_3$	28.92 kΩ
$C_6H_8O_7$	32.02 kΩ
nickel-plated steel	0.35 Ω

Table 2 Electric resistances of NaCl electrolyte of various saturated percentage

Saturation percentage, %	Electric resistance, kΩ
100	25.26
80	140.67
60	210.93
40	235.54
20	260.24

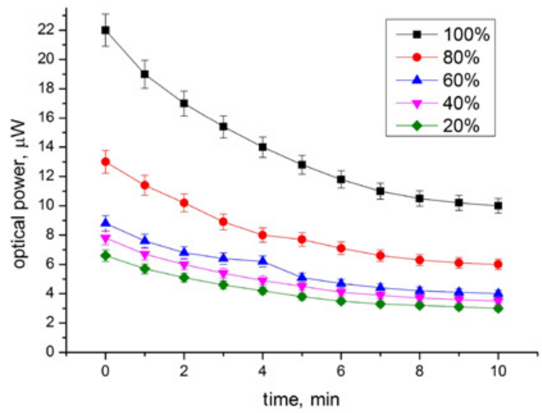

Fig. 3 *Optical power of LED using NaCl electrolyte conductors of various saturated percentages*

5 mm from the LED. The main heat transfer processes include the heat sink at the LED bottom, the natural convection in atmosphere, and the forced convection of the electrolyte. The temperatures measured at the various positions using NaCl, $NaHCO_3$, and $C_6H_8O_7$ as electrolytes are shown in Figs. 4*a–c*, respectively. The temperature tendencies for the three electrolytes were almost the same. The room temperature was the lowest. The temperature tendency at the bottom of the microfluidic chip was similar to that of the electrolyte in the microfluidic chip channel exit, and the temperature at bottom of the microfluidic chip was slightly higher than that of the electrolyte in the microfluidic chip channel exit. The temperatures at the bottom of microfluidic chips using three electrolytes are illustrated in Fig. 5*a*. The temperature at the bottom of the microfluidic chip using the $C_6H_8O_7$ electrolyte was the lowest, and the temperature of the NaCl electrolyte fluid chip was similar to that of the $NaHCO_3$ electrolyte fluid chip. The optical powers of the LED using the three electrolytes are shown in Fig. 5*b*. The optical power of the LED using the $C_6H_8O_7$ electrolyte was the lowest and the LED went out after 480 s. The optical power of the LED using the NaCl electrolyte was the highest. With respect to the temperature, optical power, electric resistance, and stability, the NaCl electrolyte was chosen as the main liquid conductor.

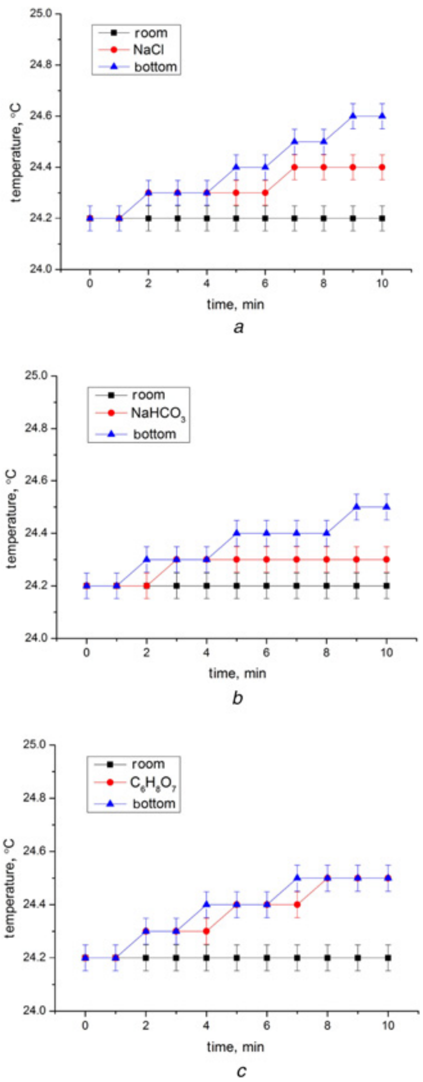

Fig. 4 *Temperatures measured at the various positions*
a NaCl
b $NaHCO_3$
c $C_6H_8O_7$

3.3. Comparison between solid and liquid conductors: A voltage of 3 V was supplied to the LED using the solid conducting wire. The temperatures at the bottom of the microfluidic chip and at room are shown in Fig. 6*a*. The room temperature was stabilised at 24.2°C.

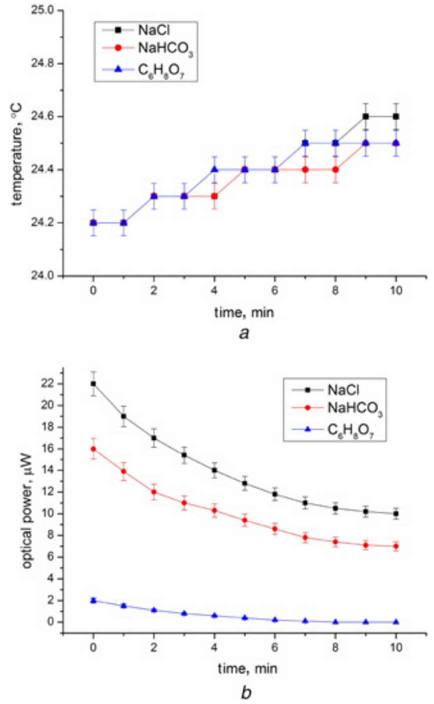

Fig. 5 *Temperatures of the bottom of microfluidic chip and optical powers of LED using various electrolyte conductors*
a Temperature of the bottom of microfluidic chip
b Optical power of LED

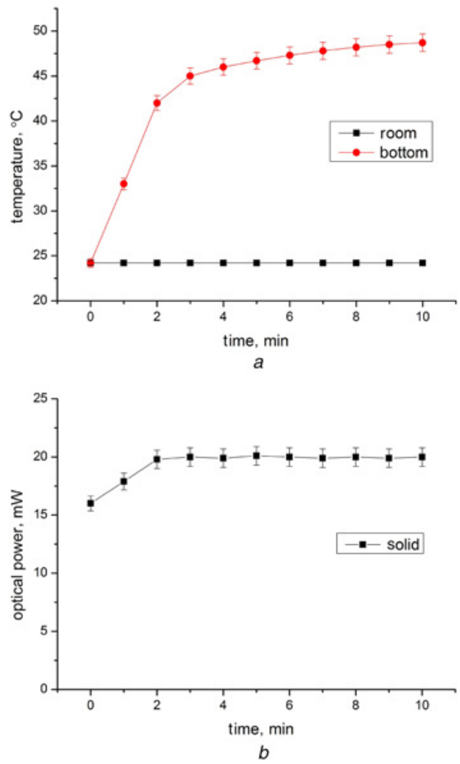

Fig. 6 *Temperatures of the bottom of microfluidic chip, room, and optical powers of LED using solid conducting wire*
a Temperature
b Optical power

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The temperature at the bottom of the microfluidic chip using the solid conducting wire increased to more than 48°C with increasing time. The optical powers of the LEDs are shown in Fig. 6*b*. The optical power increased gradually before 180 s and stabilised at 20 mW after 180 s. The results of the solid and NaCl electrolyte conductors are compared in Figs. 7*a* and *b*. The temperature at the bottom of the chip using the solid conducting wire was 24°C higher than that using the NaCl electrolyte conductor. The optical power of the NaCl electrolyte conductor LED was much lower than that of the solid conducting wire LED. Therefore, the heat dissipation of the system using the NaCl electrolyte conductor was much more effective than that of the system using solid conducting wire; however, the optical power of the LED using a NaCl electrolyte conductor was poor.

The actual voltage of the NaCl electrolyte conductor LED was different from the voltage of the power supply used in the experiment. The actual voltage of the LED was measured at various power supply voltages, as illustrated in Fig. 8. It was observed that the maximum voltage of the NaCl electrolyte conductor LED was 2.6 V when the voltage of the power supply was higher than 5 V. Furthermore, the voltage of the solid conducting wire LED decreased to 2.6 V. The results from the solid and NaCl electrolyte conductors were compared, as shown in Figs. 9*a* and *b*. The temperature at the bottom of the chip using the solid conducting wire was 4°C higher than that of the chip using the NaCl electrolyte conductor. The optical power of the NaCl electrolyte conductor LED was about 55% that of the solid conducting wire LED. However, the temperature and optical power differences between the solid and NaCl electrolyte conductors were not large. When the voltages of the system using the NaCl electrolyte and solid conducting wire were similar, the values of optical power in the two cases were also similar.

The temperature differences of LED using various cooling methods were compared, and are shown in Fig. 10. It compared the temperature difference of LED without fin and fan. The temperature difference of LED with fin and without fan was about 3°C, that of LED with fan and without fin was about 8°C, and that of LED with fin and fan reached 10°C [11]. The temperature difference of LED was about 6.5°C using heat pipe [16], and it may be larger than 20°C using a dielectric layer [14]. In our method, the temperature difference of LED reached 25°C using electrolyte. The temperature reduction of LEDs using the cooling method in this Letter was equal to or larger than the reductions using other methods.

3.4. Comparison between liquid conductors with various flow rates: Flow rates of 1.667, 3.333, and 5 μl/s were used to compare the differences between the NaCl electrolytes, as shown in Figs. 11*a* and *b*. The temperature at the bottom of the microfluidic chip is illustrated in Fig. 11*a*. The temperature decreased by increasing the flow rate is the lowest for a flow rate of 5 μl/s. Higher heat dissipation was achieved by a higher flow rate, thus lowering the

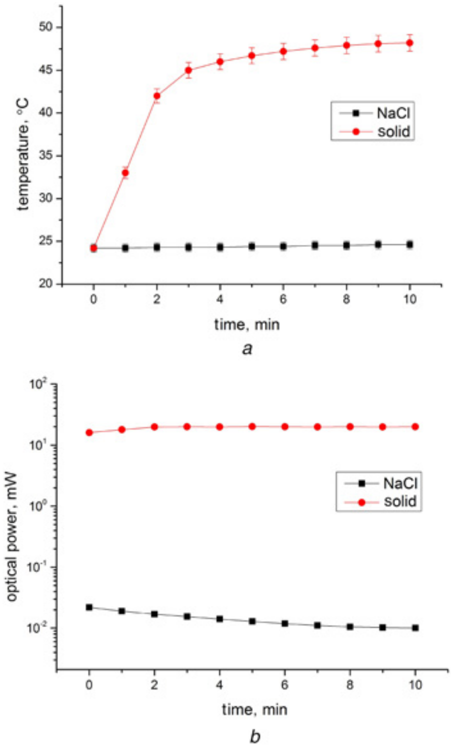

Fig. 7 *Temperatures of the bottom of microfluidic chip and optical powers of LED using solid and NaCl electrolyte conductors*
a Temperature
b Optical power

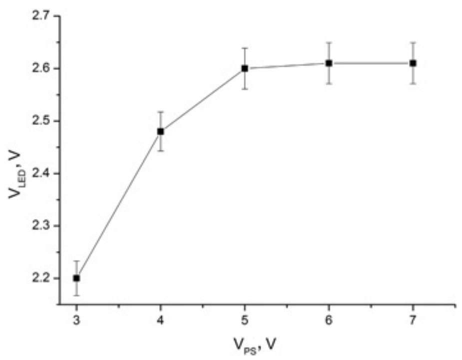

Fig. 8 *Electric voltages of LED using NaCl electrolyte conductor in various electric voltages of the power supply*

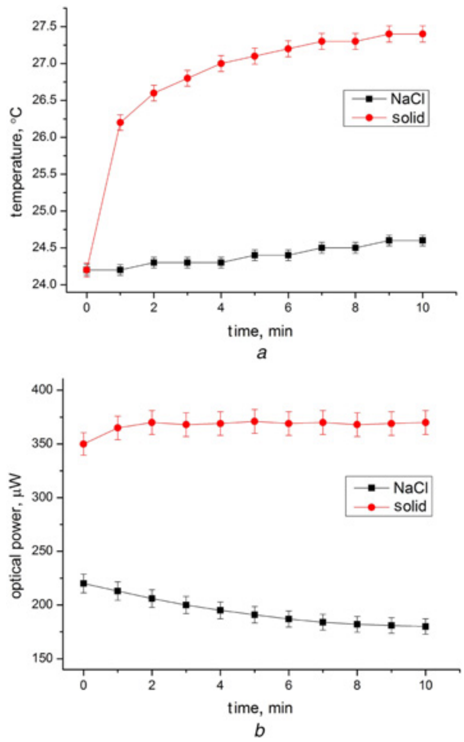

Fig. 9 *Temperatures of the bottom of microfluidic chip and optical powers of LED using solid and NaCl electrolyte conductor in electric voltage 2.6 V of LED*
a Temperature
b Optical power

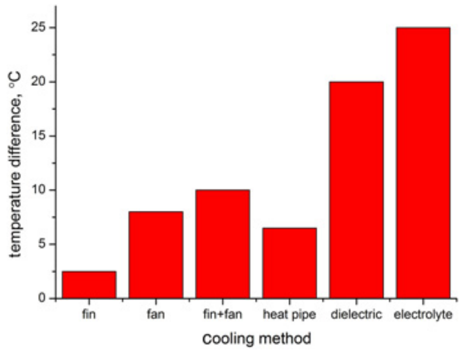

Fig. 10 *Temperature difference of LED using various cooling methods*

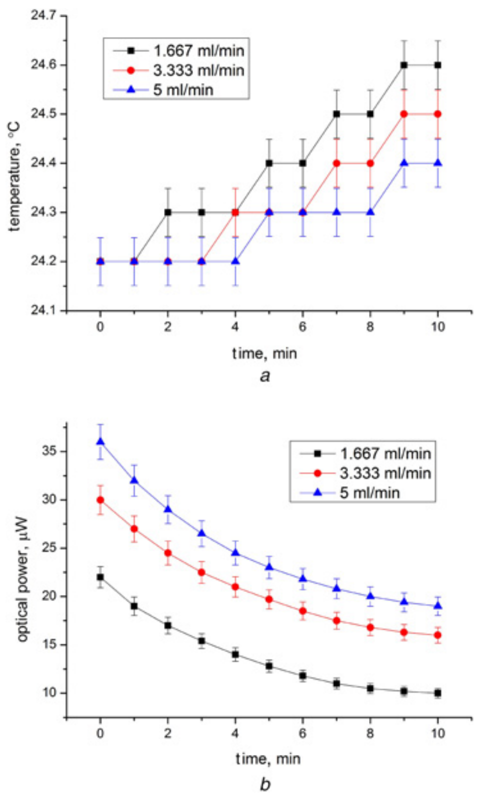

Fig. 11 *Temperatures of the bottom of microfluidic chip and optical powers of LED using NaCl electrolyte conductor with various flow rates*
a Temperature
b Optical power

temperature. The optical power is illustrated in Fig. 11*b*; the optical power increased by increasing the flow rate is the highest for the flow rate of 5 µl/s. The optical power was inversely proportional to temperature. Therefore, the optical power at 5 µl/s was higher than that at 1.667 and 3.333 µl/s.

4. Conclusions: We have proposed a method to dissipate heat and conduct electricity using a liquid conductor. Three electrolytes, NaCl, $NaHCO_3$, and $C_6H_8O_7$, were used as liquid conductors. These electrolytes dissipated heat, and the optical power of the NaCl electrolyte LED was the highest. The temperature at the bottom of the microfluidic chip using the NaCl electrolyte conductor was much lower than that of the chip using the solid conducting wire. However, the optical power of the NaCl electrolyte conductor LED was lower than that of the solid conducting wire LED. The temperature at the bottom of the microfluidic chip could be decreased and the optical power could be increased by increasing the flow rate. A liquid conductor with low electric resistance is a top priority for the future; moreover, the optical power of the LED using a liquid conductor may be largely improved. The appropriate theory of liquid conductor for dissipating heat and conducting electricity is also our future work.

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