# DC-DRIVEN ACRYLATE-COPOLYMER-BASED ELECTROTHERMAL OSCILLATOR AND ITS APPLICATION IN THERMOPNEUMATIC DIFFUSER PUMP

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## ABSTRACT

This work presents a novel electrothermal oscillator driven by a fixed DC voltage, and its application in thermopneumatic diffuser pump. The proposed device employs ultra-sensitive temperature sensing material which was made by dispersing acrylate copolymer with graphite particles. The fabricated device features advantages such as simple fabrication process, easy operating method, and simple system architecture. The periodic electric current switching for activating a nozzle-diffuser valveless thermopneumatic pump with the electrothermal oscillator was demonstrated by supplying a constant DC voltage.

## INTRODUCTION

It is well-known that strong correlation exists between crystallinity and positive temperature coefficient (PTC) effect [1]. Amorphous polymer PTC composites are hard to produce significant PTC effect because the volume thermal expansion of the polymer composites is too small to induce large resistivity change [2]. PTC phenomenon can also be observed in crystalline polymers filled with conductive particles. PTC copolymer materials have been proposed in the applications of thermistors and resettable fuses. To enable temperature-measurement applications in flexible electronics with suitable temperature ranges, research groups attempted to employ polymers as the PTC materials. Yokota et al. reported flexible sensitive thermal sensors based on the composites of semicrystalline acrylate polymers and graphite that exhibit a resistivity change around six orders of magnitude in a temperature range of about 5 ˚C [3]. Ni-microparticle-filled polymer composites were developed as temperature sensors with improved performance when compared to single polymer composites [4]. Feng et al. proposed carbon-black-filled polypropylene (PP)/ ultra-high molecular weight polyethylene (UHMWPE) composites and reported the PTC and negative temperature coefficient (NTC) behaviors of the composites [5]. In [6], carbon nanotube (CNT) filled high density polyethylene (HDPE) composites were prepared by using conventional melt-mixing methods and the PTC effects was investigated in details. Asare et al. studied the trade-off between low percolation threshold and large PTC intensity in conductive polymer composites [7].

In this work, we present a novel electrothermal oscillator by employing ultra-sensitive temperature sensor for self-switching on/off a microheater with a DC power supply. The printable thermal sensor based on composites of semicrystalline acrylate polymers and graphite. The oscillator consists of an electrothermal microheater and a PTC-copolymer temperature sensor. The temperature sensor cuts off the supply current to the microheater when the resistance of the PTC copolymer increases significantly, which in turn produce the switching behaviors. A C-shape planar heat sink is employed to speeding up the cooling process. Also, in order to demonstrate the application of the proposed electrothermal oscillator, we design and implement a DC-driven diffuser micropump integrated with a thermos-pneumatic actuator and the oscillator.

## OPERATION PRINCIPLE AND DESIGN

Figure 1 illustrates the principle of electric resistance switching of the copolymer. As the PTC copolymers reach the glass transition temperature ($T_g$), the crystallites in the polymer melt and therefore become amorphous, which results in the increase in volume. The conductive particles in the polymer are separate by the volume increase of the polymer, and thus the conductivity of polymer reduces.

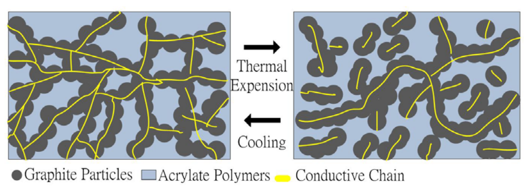



*Figure 1: The working principle of PTC Copolymer*

Figure 2 shows the schematic and the exploded view of the proposed DC oscillator device. The device consists of a microheater, a PTC copolymer sensor, and a C-shape planar heat sink. Figure 3 illustrates the temperature oscillation by using the PTC copolymer for switching on/off the heater. As the temperature increases and reaches $T_g$ by the heater, the significant increase of copolymer resistance cuts off the heater voltage, and thus cools down the system. The heating process starts again as the copolymer resistance decreases significantly due to temperature decreases. The C-shape heat sink surrounding the sensor is used for speeding up the cooling process.

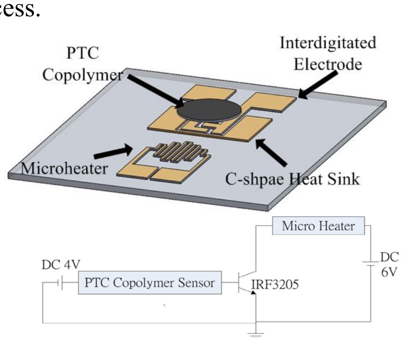



*Figure 2: Schematic of the proposed DC oscillator device*

Figure 4 shows the schematic and the exploded view of the proposed thermopneumatic micropump integrated with the proposed electrothermal oscillator (Fig. 4(a)). As shown in the figure, the micropump consists of three layers: the PDMS channel layer, the PDMS diaphragm layer, and a glass substrate with pattern electrodes. Fig. 4(b) shows the detailed dimensions of the device. The diameter of the pump chamber is 3,000µm. The width of the diffuser inlet is 100µm and the width of the outlet is 370µm. The diffuser length is 3,000µm. Previous work shows that the minimum losses of pressure occur at a diverging angle of about 5° [8]. In this work, the diverging angle is designed as 5.15°.

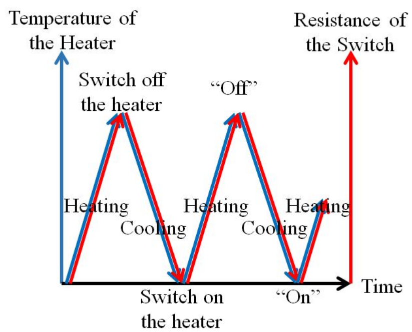



*Figure 3: Schematic of device operation*

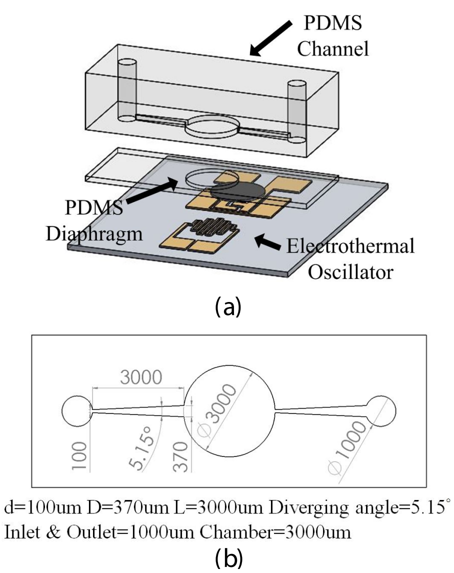



*Figure 4: (a) Schematic of pump device (b) The size of the channel*

## FABRICATION

The synthesis process of the polymer is illustrated in Figure 5. The preparation of the polymer PTC composites is as follows: semicrystalline acrylate copolymers were fabricated by polymerizing two acrylate monomers with different alkyl sidechain lengths: 20 mol % butyl acrylate (BA) and 80 mol % octadecyl acrylate (OA) with 1.0 wt% DMPA, and were dissolved in an additional 100 wt% THF. Polymerization was carried out via exposure to365-nmUV light (UVL-28ELseries, 4 W) for 1 day. Graphite particles (2–3-µm diameter), which serves as conductive fillers, were added to acrylate copolymers. The synthesized semicrystalline polymer was mixed with graphite in a weight ratio of 3:1 (polymer : graphite) using a magnetic stirrer. The organic solvent was then removed under vacuum in a desiccator for 1 day

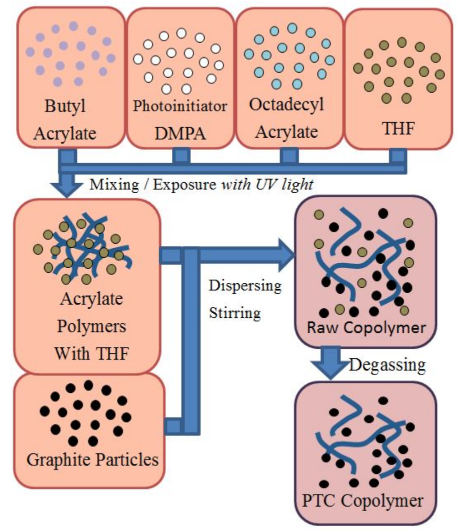



*Figure 5: The preparation of PTC copolymer*

Figure 6 describes the fabrication of the pump embedded with the proposed electrothermal oscillator. Firstly, an AZ photoresist was spin-coated and patterned on a glass wafer (Figs. 6(a)-(c)). Then, a Ti/Au layer was then deposited and patterned (Fig. 6(d)-(e)). Then, PDMS channel and diaphragm were realized by using the soft-lithography process with SU-8 molds (Fig. 6(f)-(j)). Finally, after oxygen plasma treatment, the device was assembled. The copolymer with filler was printed onto the interdigitated electrode on a hot plate of 60˚C, using a 55µm-thick polyimide tape as a spacer (Fig. 6(k))

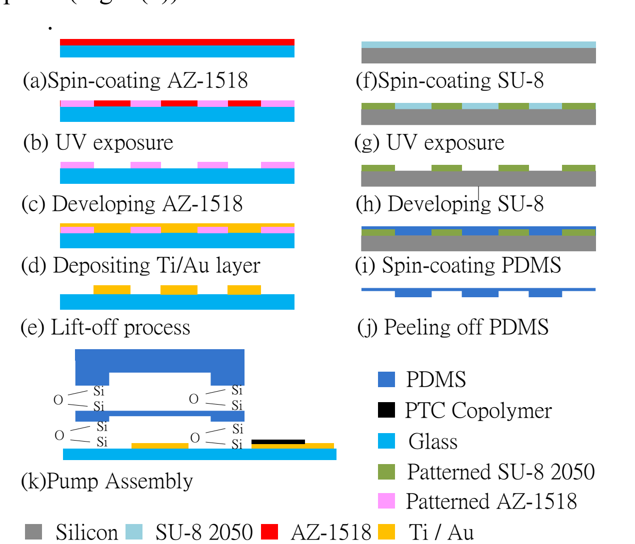



*Figure 6: The fabrication process of the proposed thermopneumatic diffuser pump device.*

Figure 7 shows the pictures of the fabricated devices. Fig. 7(a) is the bottom layer with the patterned micro heater, interdigitated electrode, and the C-shape heat sink. Fig. 7(b) shows the fabricated PDMS diaphragm layer. The thickness of the layer is 200μm, and the thickness of the diaphragm is 50μm. Fig. 7(c) is the fabricated PDMS channel layer with punched holes. The channel layer thickness is 5mm, and the channel height is 150μm. Fig. 7(d) shows the assembled device.

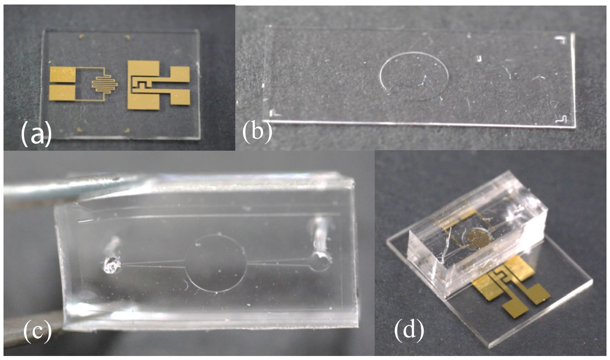
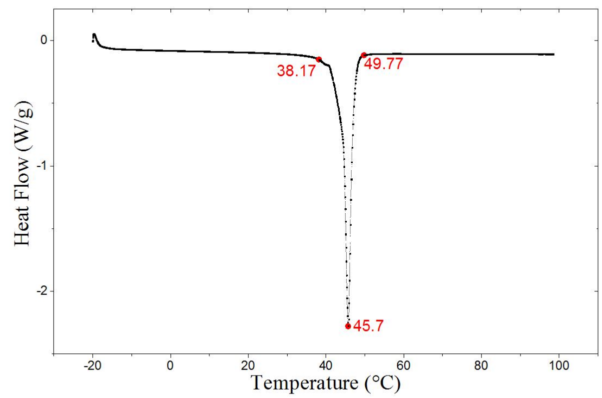



*Figure 7: The fabrication results: (a) the bottom layer, (b) the PDMS diaphragm layer, (c) the PDMS channel layer, and (d) assembled device.*

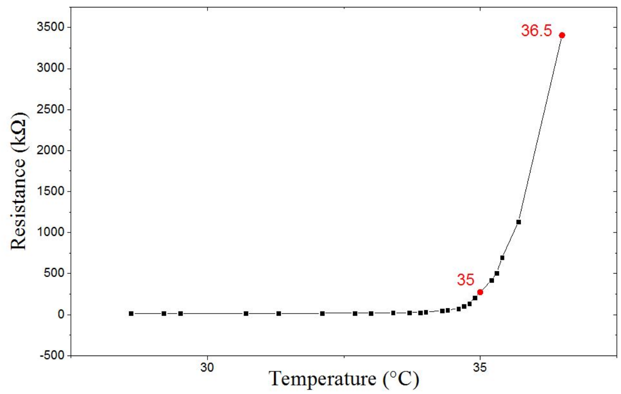
## MEASUREMENT AND DISCUSSION

Figure 8 shows the measured characteristics of the synthesized PTC copolymer material. Fig. 8(a) shows the melting point which was determined by DSC endotherm. The copolymer has a melting point of 45.7˚C, whereas the switch exhibit the highest sensitivity near 35˚C.The electrical characteristic of films is shown in Fig. 8(b). The thermal sensor exhibits the initial resistance changes of four orders of magnitude over a temperature change of only 1.5 ˚C.

Figure 9(a) shows the photo of the finished pump product. Polyvinyl chloride (PVC) tubes are connected to the inlet/outlet and electrical wires are soldered to the pads of the heater and the PTC switch. The outer diameter of the PVC tube is 1mm, and the inner diameter is 0.5mm. Fig. 9(b) illustrates the experimental setup for measuring the flow rates. The fluid meniscus displacement in the tube connected to the outlet is recorded by a digital video camera. The voltages applied to the micro heater and the PTC copolymer sensor are 6V and 4V, respectively. A source meter was employed to measure the resistance of the PTC copolymer sensor. A K-type thermocouple was used to measure the temperature near the microheater. Figure 10 shows the measured transient temperature oscillation of microheater with a fixed DC voltage of 6 volts. The amplitude of the oscillation is about 8˚C (Fig. 10(a)). The frequency of oscillation is about 0.05Hz. Fig. 10(b) shows the series photo of fluid pumping. The meniscus displacement of the fluid in the tube is 1.54mm in 10s. The flow rate is about 1.813μL/min.

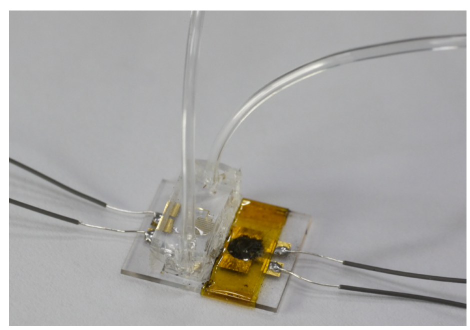



(a)

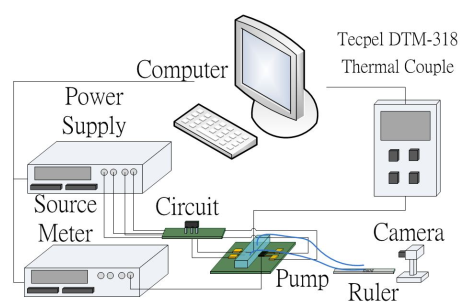



(b)

*Figure 8: (a) The DSC melt endotherms of the copolymer with filler. (b) Temperature dependence of the resistivity of the copolymer with filler.*

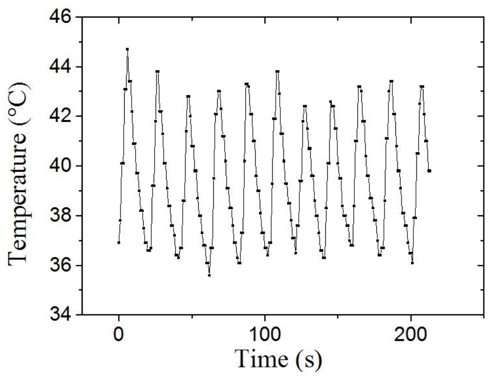


(a)

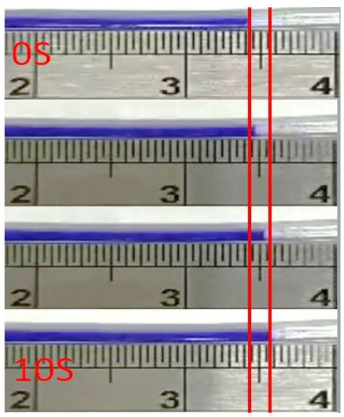



(b)

*Figure 9: (a) Fabricated thermopneumatic diffuser pump (b) Experimental setup*




(a)




(b)

*Figure 10: (a) The transient behavior of micro heater with DC voltage (b) The series photo of fluid pumping*

## CONCLUSION

This work presents a DC-driven electrothermal oscillator with ultra-sensitive temperature sensing acrylate copolymer. The oscillating behavior is achieved by self-switching on/off a microheater using the temperature sensing copolymer. The measured results show that the thermal sensor possesses ultra-high sensitivity. The resistance variation is about four orders of magnitude over a temperature range of only 1.5 ˚C. Stable temperature oscillation produced by the oscillator was observed. Also, a nozzle-diffuser micropump integrated with the proposed oscillator was demonstrated.

## ACKNOWLEDGEMENTS

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