

Programable hierarchical actuation schemes based on phase change composites arranged as a resistive network

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Summary:

In this contribution we present a concept for the utilization of an electrically conductive phase-change composite as a drive element for the realization of predefined and programmable micro-actuation schemes in space and time. For this purpose, segments of a composite of paraffin and carbon black with different cross-sectional areas are arranged in a predefined pattern, reflecting a resistive network. Applying electric current to this network triggers an actuation pattern defined in space and time that can, for instance, be used for complex actuation sequences in microfluidic chips.

Keywords: functional composites, phase change actuator, paraffin, carbon black, transducer network

Introduction

Phase-change materials based on paraffin have been widely used in various actuation schemes, in most instances confined within a small cavity and with an attached heater to gain control over temperature and thus the volume-change actuation mechanism associated with the phase transition from solid to liquid [1]. In a few studies the paraffin wax itself was made accessible for Joule heating by adding conducting particles [2]. Here, we advance this approach by arranging conductive paraffin as a resistive network, enabling predefined, sequential actuation schemes embedded in a single platform.

The Phase Change Composite

Carbon Black (CB) was added to pure paraffin wax (PW) in the molten state, well above 55 °C, until the resulting bulk composite featured a base resistance of approximately 10 kΩ at room temperature (~25 °C) when measured at a thick layer with probe tips with a 10 mm spacing.

Subsequently, the PW/CB composite was characterized with respect to its temperature behavior, with results shown in Fig. 1. As expected, the composite undergoes the solid-to-liquid phase change at around 50 °C, accompanied by a steep increase in electrical resistance. This is anticipated since, due to the volume increase, the average distance, and hence the overlap between conducting particles decreases, thus reducing the available electrical pathways and the electrical conductivity.

However, for temperatures well above 50 °C the electrical resistance of the liquid composite

decreases again, although the volume still increases at a low rate. This effect is most likely attributed to electrophoretic migration and alignment of carbon particles in the liquid paraffin, as has been examined previously [3].

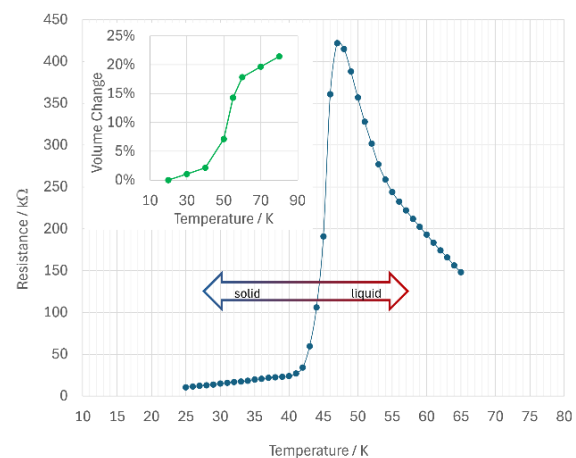


Fig. 1. Electrical resistance over temperature of the utilized PW/CB composite measured in the bulk with the probe tips featuring a distance of 10 mm. The inset shows the corresponding volume change determined separately via a volume displacement measurement.

The Operating Principle

The basic idea is to arrange conductive segments made of the devised composite with different cross-sectional areas and hence electrical conductivity in such a way that a resistive network is formed. Applying Joule heating to this network then leads to local heating and hence volumetric expansion, initially at the points of highest ohmic resistance. According to the chosen dimensioning of the single segments and

their arrangement relative to one another, a predefined hierarchical sequence of volumetric actuation can be released on demand.

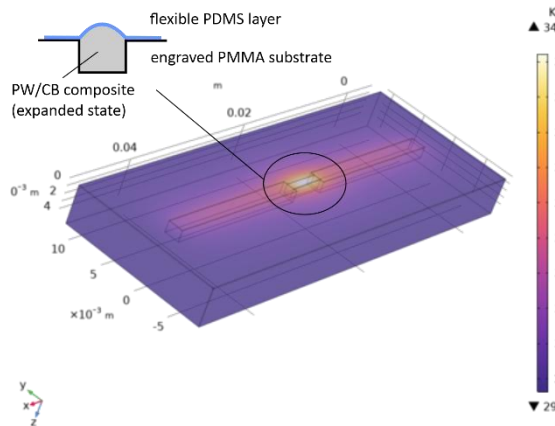


Fig. 2. FEM simulation (Comsol Multiphysics) illustrating the localized Joule heating effect at a geometric restriction of the PW/CB composite structure.

This actuation cascade, geometrically and chronologically predefined and reversible, can be utilized, e.g., for peristaltic actuation of fluid in an attached chip with an engraved fluid channel, as microfluidic switches or flow meters in general, or can be transformed into any other kind of mechanical displacement.

Proof of Principle, the first Actuation Chips

Fig. 3 shows, as proof of principle, the same geometry as in the simulation in Fig. 2, realized with laser-engraved channels in a PMMA substrate, filled with the PW/CB composite, and sealed with a thin elastic PDMS layer on top. In accordance with the geometric dimensions of the line segment ($1 \times 0.8 \times 5 \text{ mm}^3$) and the measured volume expansion coefficient, as illustrated in Fig. 1, the achieved membrane deflection amounts to $\sim 0.3 \text{ mm}$ shortly after onset of the Joule heating due to the applied electric current.

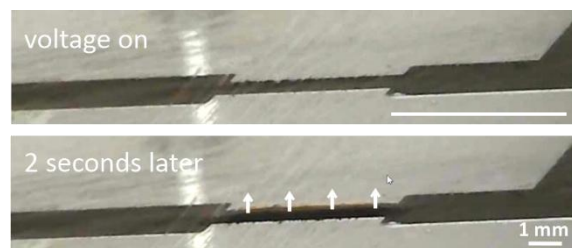


Fig. 3. Proof of principle, showing the volume expansion-induced deformation of a thin PDMS layer above the geometric restriction of the PW/CB structure directly after the onset of Joule heating (side view).

As a next step, a peristaltic actuation scheme from the center outward was examined by joining together segments with increasing cross-section.

Applying current to this structure leads to a kind of peristaltic deformation of the elastic membrane on top, as illustrated in Fig. 4.

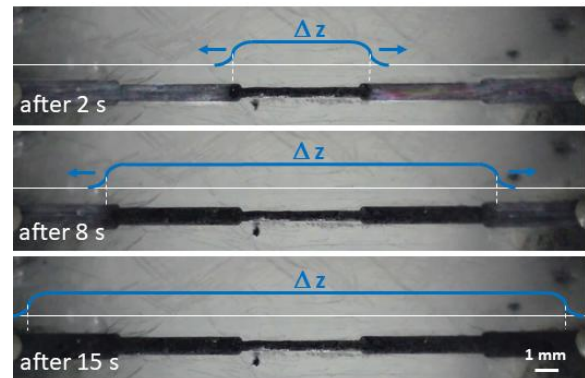


Fig. 4. Peristaltic deformation center outward of the covering PDMS layer on top, achieved with symmetric alignment of segments with different cross-sectional area (top view; expanded section indicated for better visibility).

Response time and actuation dynamics, as indicated in Fig. 3 and 4, strongly depend on the applied electric power and have not yet been examined in detail.

Conclusions and Outlook

In summary, it has been shown that an electrically conductive phase-change composite, arranged in connected segments as a resistive network, can be used to realize complex micro-actuation schemes predefined in space and time. For example, multilocal actuation can be implemented on a single microfluidic chip, either time-delayed or sequentially, as shown for the peristaltic membrane deflection in Fig. 4, or simultaneously at different spots for, e.g., switching and valving. Layout and dimensioning of the single segments for a specific actuation pattern are straightforward, since they simply reflect a resistive network subjected to ohmic heating as soon as a voltage or current source is activated.

A further degree of freedom in design can be achieved by combining the conductive composite segments with low-ohmic metallic lines in between in hybrid technology. This can, for example, be realized by using a standard PCB as the initial substrate and combining copper-based conductive paths with engraved and phase-change-composite filled channels.

References

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