A portable device for temperature control along microchannels

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For many physical, chemical and biological measurements, temperature is a crucial parameter to control. In particular, the recent development of microreactors and chip-based technologies requires integrated thermostatic systems. However, the requirements of disposability and visual inspection of a device under a microscope cannot accommodate equipment such as external heaters. By exploiting a silver-filled epoxy that can be injected and solidified in a microfluidic chip, we demonstrate a simple and inexpensive design of a conductive path, which allows heating by the Joule effect of both sides of a microchannel. In addition to permitting the maintenance of a constant temperature along the channel walls, our method can control the temperature gradient across the channel, thus enabling non-equilibrium studies in a microfluidic geometry.

Introduction

Microfluidic lab-on-chip devices are usually designed to mimic on a much smaller scale operations performed in a standard laboratory, with the significant bonus of greatly reducing the amount of sample and the time needed to perform a specific task.[1] Yet, many practical situations, in particular when dealing with biomedical materials, require careful control of environmental parameters in order to set reproducible protocols. Although control of pH or the chemical environment more generally poses no serious problem to downsizing standard protocols to the microfluidic scale, thermal control faces a number of challenges. We address this issue here using a conductive epoxy that can conform to the shape of a microchannel.

The difficulties in thermal control for microfluidics arise in several contexts. For example, the poor thermal conductivity of materials such as PDMS, or other elastomers used in devices made by soft-lithography, makes it difficult to design an efficient and fast external temperature control. Performing internal thermal control is also challenging, since, in addition to requiring reliability and ease of operation, the thermal design must be small and follow the channel geometry as closely as possible without hindering visibility. Last but not least, the approach should have a limited cost since many devices are designed to be disposable.

Depending on the particular needs, temperature control can be achieved by using different methods: one approach is to use external Peltier modules, as in the temperature gradient focusing (TGF) technique[2] or DNA amplification,[3] but then it is not easy to simultaneously use microscopy to make observations. Another way is to use exo- or endothermic chemical reactions between solvents,[4] but in this case no tunable temperature is achievable. Other techniques involve the use of hot and cold water flow,[5] resistive heaters made of Pt and Ti,[6,7] boron-doped polysilicon[8] or silver paint,[9] flexible printed circuits,[10] irradiation by infrared light[11] or microwaves;[12,13] in all cases these devices require complex fabrication processes or cannot be considered completely portable. In this note we show that a tunable heater matching all of the above requirements and which is directly embedded in a microfluidic chip can be designed and exploited.

Experimental device

We used polydimethylsiloxane (PDMS) to fabricate our device. A great number of advantages make PDMS the most popular material employed so far in microfluidics: biocompatibility, ultraviolet transparency, permeability to gases, and simple fabrication, just to name some. Even the limited compatibility with organic solvents can be easily overcome by coating the channels with a glass-like layer.[14] Moreover, while the low thermal conductivity of PDMS (0.15 W m^{-1} K^{-1}) has a negative impact on external temperature control, it turns out to be a significant advantage for internal heating strategies since, by minimizing undesired energy losses, efficient heat transfer to a channel closely contacted to the heat source is guaranteed. In addition, the high electrical resistivity (about 4×10^3 Ω m) allows exploiting Joule dissipation to provide energy *via* an embedded electric heater. Thus, we have designed a conductive strip that follows the microchannel and surrounds it at a fixed distance. By applying a voltage ΔV between the two extremes of the conductive layer we are able to maintain the channel at a desired temperature.

The PDMS channels were prepared by replica molding and sealed to a thin glass slide (or other PDMS) using standard soft-lithography techniques.[15] Then, we filled the empty heater channels with a silver-filled two component epoxy (Epo-Tek® H20S, Epoxy Technology), that, owing to its moderately low viscosity (1800–2800 cP at room temperature), can be injected, after mixing the two parts, and made to flow in the co-running channels using a syringe. Once the channel is carefully filled,

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maintaining it at a temperature slightly higher than room temperature to avoid a non-uniform filling, the epoxy is solidified by keeping it above its glass transition temperature (80 °C) for about 1 h. The drawing in Fig. 1 displays the device containing two separate epoxy-filled ducts (2 mm width, 25 μm height and 40 mm length) that surround, at a distance of 100 μm, a thin central channel (75 μm width and 25 μm height) where the sample to be investigated is injected. The cross-sectional view shows the microchannel, the two co-running heating channels, and the thin glass cover plate. While the epoxy is cured, each channel used for thermal control is contacted by thin wires allowing for independent operation of the two heaters during use; the dual control also allows us to impose temperature gradients across the sample channel.

The novelty of our approach is to use a thermosetting conductive polymer so that the heater shape can easily follow the geometry of the sample channel. A similar idea has been exploited with ionic liquids[16] or a solder metal[17] as heating media. While the former case requires high ac voltages (∼kV), in the latter the use of liquid metal may present problems close to the melting temperature. Instead our device, once cured, permits working continuously from $T = -55$ °C to 200 °C (or intermittently till 300 °C). In addition the current required by our system (given the same power) is lower, due to the resistivity of the epoxy, which is ∼70 times higher than that of In100 (the solder metal used in ref. 17). These features have allowed us to use two ordinary AAA batteries to heat up a microchannel with our method.

Once the silver-filled epoxy is cured, its electrical conductance is quite high. For the specific geometry we selected, the total electric resistance of the channel is $R = \rho L/S$, where $\rho \approx 5 \times 10^{-6}$ Ω m is the resistivity of the epoxy, L is the length of the conductive channel (ranging in our case between 0.04 and 0.08 m), and $S = 5 \times 10^{-8}$ m^2 is the cross-sectional area of the strip; thus we estimate $R \approx 6$ Ω. In practice, moderate variations in R between different device realizations can be expected, since the actual resistance depends crucially on the total amount of resin filling the channel. Each heater is calibrated by plotting both the dissipated power, $P = I^2R$ and temperature, T, reached by the conductive strip *versus* the input current I. To measure the latter, we used a thermistor in thermal contact with the thin (0.17 mm) glass cover slip, which was thermally insulated from the external environment by an additional PDMS layer. The measured T differs from the real temperature of the strip because of the resistance across the glass thickness, which yields a temperature drop, neglecting conduction through the PDMS, of $\Delta T \approx \Delta P l/(kA)$, where $k = 1$–1.4 W m^{-1} K^{-1} is the thermal conductivity, l is the thickness and A is the cross-sectional area of the glass slide. This estimate for ΔT ranges from 0.3 °C to 2 °C when the temperature of the heater reaches 30 °C and 75 °C, respectively. Typical calibration curves are shown in Fig. 2 and the reproducibility has been checked. Once current is applied, the temperature increases within 10–20 s, reaching a stable state in less than 1 min.

We next investigate different geometries for the thermal control for regulating the temperature variations in the sample channel. Fig. 3 shows two different geometries of the conductive strip: the first (a) is one of the two linear conductive channels that lie next to the central microchannel shown in Fig. 1 (the other one was omitted to better show the temperature behavior), while the second (b) is designed to maintain the channel at a constant temperature with a single voltage input by surrounding it with the heater. The same figure shows, however, that, at least at high current (the plots are obtained for both devices at $I = 500$ mA), the temperature distribution is not uniform and it has a maximum close to the connection wires. A substantial temperature decrease is indeed evident both in the middle of the channel (Fig. 3a) and in the region furthest from the connections of the encircling channel (Fig. 3b). We observed the same outcome with a linear strip of epoxy which discards the hypothesis of effects associated with corners. Other explanations might be a non-uniform filling of the epoxy inside the channel

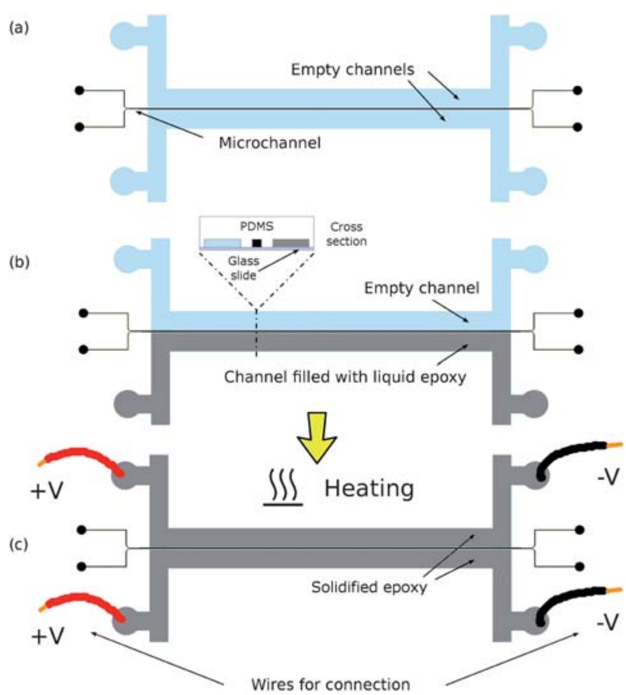

Fig. 1 A schematic of the device: the empty channel (a) is filled with a conductive epoxy (b), which, after inserting wires for the electrical connection, is heated until the epoxy solidifies (c).

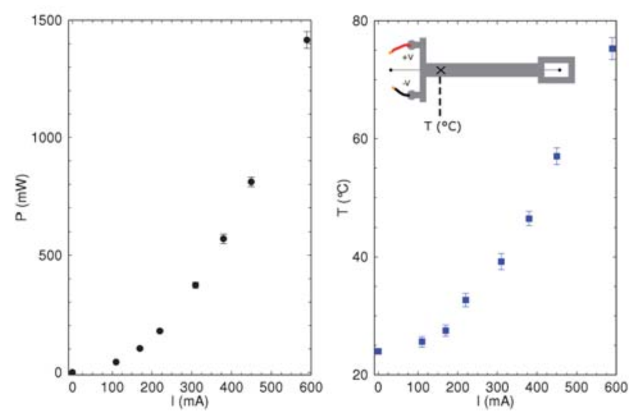

Fig. 2 Typical relation between current and dissipated power (left-hand panel) and between current and temperature achieved (right-hand panel). The position where the temperature is measured is also shown.

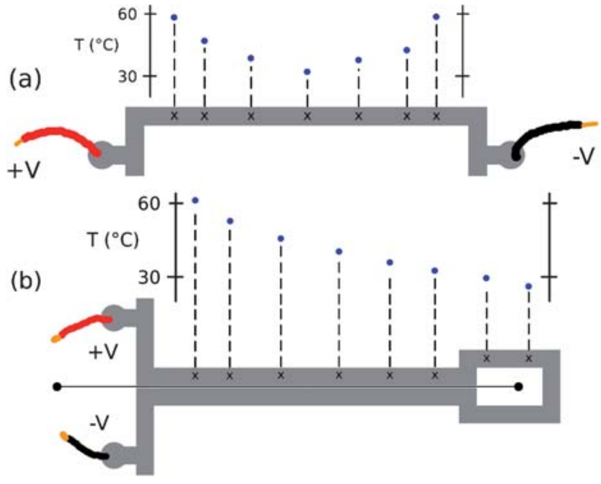

Fig. 3 Temperature (shown by dots) along the channel filled with the epoxy in two different geometries: (a) one of the heater shown in Fig. 1 and (b) a variant in which one heater surrounds the microchannel. In each design the temperature exhibits a non-uniform distribution. Error bars fall inside the dots.

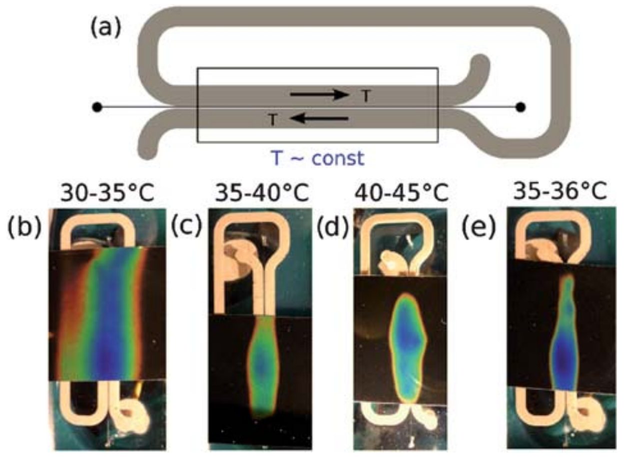

Fig. 4 (a) A version of the device able to maintain a constant temperature in the test channel. (b–d) 5 °C range sheets, as stated upon each image, to show different temperatures gained for different bias currents. (e) 1 °C sensitive liquid crystal sheet ranging from 35–36 °C: it is clear that there is only a small variation of temperature along the microchannel.

or non-negligible contact resistance between the epoxy and the leads.

To eliminate this drawback‡ we compensated for the longitudinal thermal gradient by winding the conductive strip back to its starting point, and placing the sample microchannel in between the back and forth paths of the heater (Fig. 4a). This design produces a large and fairly constant temperature region.

To directly visualize the temperature profile along the channel, we used Mylar liquid crystal sheets (Edmund Optics) with a spatial resolution of about 3–5 μm. The color displayed by these sheets turns from red to dark blue, passing through yellow, green, and light blue, by increasing the temperature by 5 °C, while the sheets are black outside the working temperature range. Fig. 4b–d show the temperature distribution for different input currents. The relation between I and T is the same as presented in Fig. 2 with similar absolute values. Furthermore, nearly isothermal regions can be mapped accurately by monitoring the color pattern using images obtained with a higher sensitivity sheet where the whole chromatic range occurs for a temperature change of just 1 °C (see Fig. 4e for results from 35–36 °C). The results show an almost uniform temperature along the channel (within 2–3 °C in the zone highlighted by the box in Fig. 4a) for all of the investigated temperature ranges. The stability of the temperature *versus* time is about 2% over several hours. We are currently exploiting such a device to investigate microfluidic separation based on thermal diffusion,[18,19] by imposing a temperature gradient across the microchannel.

‡ Another way could be varying the cross-sectional area of the resistive heater, as suggested by one of the referees.

Conclusions

A fully embedded technique to control temperature in elastomeric microfluidic devices has been developed. Beside its portability, the main features are the cost-effectiveness and the ease of fabrication that lead to its ready use when the control of the temperature is a crucial parameter in a microfluidic design. One of the distinctive characteristics of our device is the possibility to maintain a specified temperature in a microchannel instead of a closed chamber, so as to perform microfluidics experiments that exploit the temperature dependence. Moreover, a portable, inexpensive and low-power on-chip thermal control would be useful in resource-poor environments or developing countries, where microfluidics can have a great potential impact for diagnostic technologies.[20]

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