Pencil trace on cellulose compounds: a heat source

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This communication describes a low-cost heater designed and fabricated from materials like paper/cellulose acetate sheet and a pencil. A high graphite content pencil was used to coat the surface of paper/cellulose by applying sufficient strokes on the surface. Electrical contacts were made by placing either a wire or copper/aluminium foils over the coated surface. Temperature profile study of the heater indicated that a maximum of 100°C can be achieved without the paper catching fire. The heater was also designed in flexible structure and tested for biomedical purpose. The heater can be operated using a battery, making it easily portable. This makes it useful in school, college and research laboratory experiments with minimum expenses as well as in many medical applications as described.

Keywords: Pencil trace, cellulose compounds, heat source, graphite composite.

PAPER-BASED low-cost devices have elicited significant attention in recent years. In this communication, we describe a medium of deposition through mechanical abrasion of graphite-based pencil on paper. This fabrication process is simple yet efficacious. Pencil is basically a composite made of graphite and kaolin, which is a clay material acting as a binder[1–3]. Cellulose-based compounds like paper and cellulose acetate (CA) have proved to be effective substrate materials owing to their properties like flexible and ubiquitous nature, cost-effectiveness and compatibility towards deposition techniques.

Consequently, many paper and 'pencil on paper' devices have been realized on paper substrates in diverse areas of application such as sensors[4,5], microfluidic devices[6–8], strain gauges[9,10], R–C filters and FET[11], and printed circuit technologies[12,13]. The advent of graphene and 3D graphene has effectively broadened applications of carbon-based devices in diverse domains like catalysis, photocatalytic studies, sensors and energy applications[14]. Pyrolitic graphite has been used in rapid heating applications[15].

Here we report the design and fabrication of a heater based on pencil strokes on paper and CA. The heating element was fabricated by mechanical abrasion of graphite composite from soft-grade pencils onto the paper/CA sheet. Next, the *I–V* characteristics of the heater and temperature profiles were studied. The maximum temperature attained with this heater was 100°C with varying input power. The heater was successfully implemented in applications pertaining to research laboratories and therapeutic domains. Further the entire heater assembly was also tested for its portability feature. Our results provide an economically viable yet effective heater fabricated under ambient conditions through a simple and fast fabrication process, eliminating any need of high-end instrumentation.

The substrate materials used in fabrication of the heater were readily available notebook paper (average thickness measured using micrometer screw gauge – 74.7 μm) and CA sheets (thickness 100 μm), commonly known as transparency sheets used in a overhead projector (OHP). The pencils used were 9B grade. The paper and CA sheets were cut into area of size 2″ × 1.5″. Both were covered with pencil strokes to obtain a conductive surface. One major difference in the above two substrates was that the CA surface was roughened using sand paper for adhesion of graphite film onto its surface (Supplementary Figure 1 *a*). Binder clips were used to hold the entire heater assembly (Supplementary material 1.3). Figure 1 shows the cross-sectional view of sequence of layers in the structure of the heater.

The repeatability in the base resistance measurements and gravimetric analysis (Supplementary material 1.4) for estimating graphite content were carried out repeatedly for the graphite-coated substrates. It was observed that for an average graphite loading of 6–10 mg, the base resistance was in the range 10–30 Ω. Thus, higher the graphite content on the substrate, lower will be its resistance.

A resistance temperature detector (RTD), based on a PT-100 sensor (platinum resistance temperature sensor), which was calibrated using another standardized RTD[16] (Supplementary material 1.1 and Figure 2) was used. Uncoated paper and CA sheets were tested for their usability as a substrate for the heater material at 100°C (Supplementary material 1.2). The temperature profile of the heater was tested by applying a voltage sweep (voltage source with current limit – Agilent E3631A) and checking the corresponding current through the heater. The temperature of the heater surface was monitored (Agilent U1252B multimeter) by measuring resistance of the PT-100 sensor placed on the thermally conductive substrate.

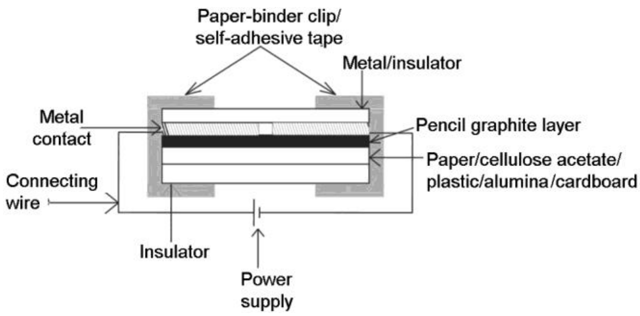

Figure 1. Basic structure of the heater assembly.

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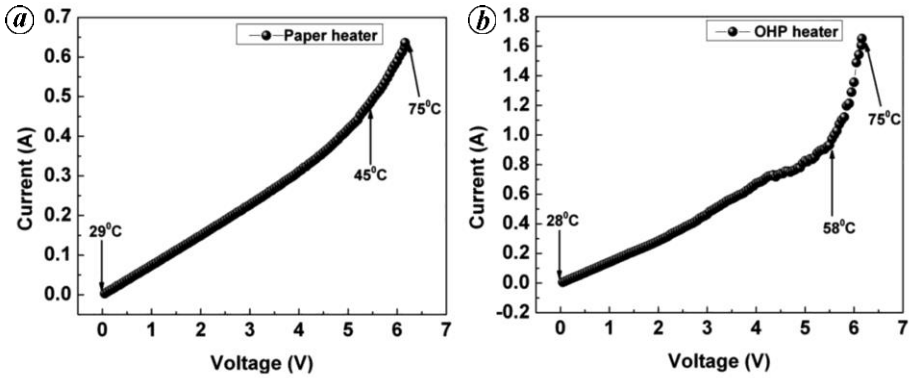

Figure 2. ***a***, *I*–*V* characteristics of the heater on (***a***) paper substrate and (***b***) cellulose substrate.

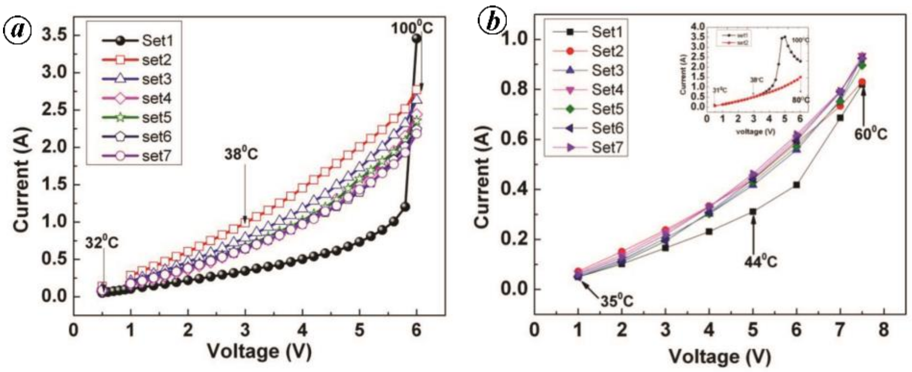

Figure 3. ***a***, Cyclic *I*–*V* characteristics of paper heater at 100°C. ***b***, Cyclic *I*–*V* characteristics of cellulose acetate (CA) heater at 60°C. (Inset) *I*–*V* characteristics for CA at 100°C.

I–*V* characteristics were cycled for both paper and CA heater structure to ensure repeatability.

The electrical characteristics of the heater were studied by the *I*–*V* characteristics (Figure 2). The typical value of (single paper/CA) base resistance for the heater was in the range 15–20 Ω. The *I*–*V* curve exhibited almost linear nature in the initial region (0–5 V), while above 5 V the current increase was rapid. The curve became nonlinear due to rapid increase in overall conductivity of graphite composite film, as also reported in an earlier study[11].

This characteristic of increased conductivity with temperature for graphite composite or pencil trace is favourable in our heater application, as it helps in increasing the heating rate at a given bias. Consequently, we get higher temperature at a relatively low power input. Such high temperature can be safely maintained for about 40 min.

We have studied the heating characteristics for graphite composite trace on paper (Figure 2 *a*) as well as CA substrate having double-heater structure (Figure 2 *b*; Supplementary material 1.3). It was observed that when voltage was increased, there was increasing current through the heater which heated up the surface in a more or less linear fashion. The final temperature achieved through heating was just over 100°C. The rapid nonlinear increase in the current was restricted using the on-board current limit facility of the voltage source (Agilent E3631A). The current limit can also be achieved by using commonly available simple transistor based current limit circuits.

Figure 3 *a* and *b* shows the repeatability of double-heater structure for paper and CA heater respectively (Supplementary material 1.3). They were tested for the *I*–*V* characteristics and final temperature by cycling applied voltage across the heaters. The paper-based heater showed maximum temperature of 100°C. A pristine CA-based heater attained 100°C, followed by reduction in final temperature (≈20%; inset Figure 3 *b*) in the subsequent cycles (Supplementary material 1.5). Nevertheless, the CA heater was found to be stable at around 60°C up to 15 cycles (Figure 3 *b*).

Many heaters have been fabricated from paper and CA substrates, and their reproducibility has been studied. Analysis was done by comparing their maximum attained temperatures. Figure 4 shows temperature values obtained using different heaters. Generally, for all the paper heaters, maximum temperature attained was around 100°C, whereas the CA-based heaters showed varied maximum attained temperatures. The reason for such deviation can be attributed to the process of surface roughening. Since the roughening is done manually, the available surface for coating graphite will also be non-uniform. As such there will be uncontrolled variation in

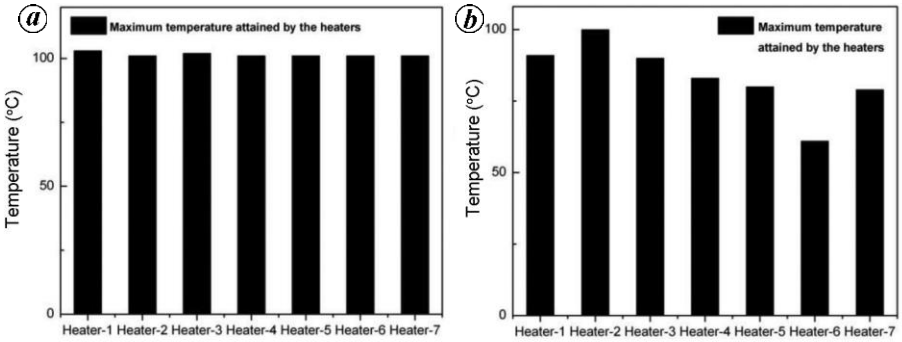

Figure 4. Reproducibility characteristics of heaters made from (***a***) two paper substrates and (***b***) two CA substrates.

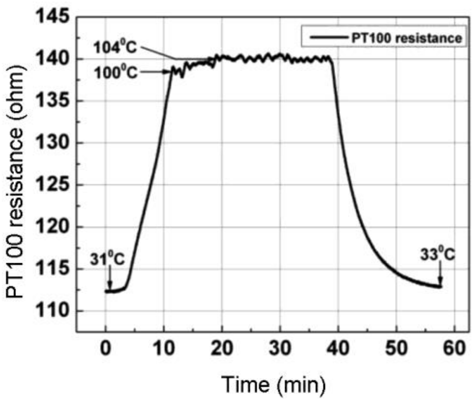

Figure 5. PT-100 resistance and time profile for double paper-based heater.

the resistance, which will in turn decide the maximum temperature that can be attained by any heater.

The paper-based heater showed good repeatability in attaining temperature around 100°C. Hence its temperature–time profile was studied to determine how long the heater can sustain 100°C. Figure 5 shows the increase in resistance of PT-100 with time for *I–V* values (which were manually controlled) analogous to range as specified above. The average maximum temperature obtained was 104°C. It was maintained for (≈40) min without any signs of burning on the paper substrate.

The fabricated heater structure was tested for elevated-temperature chemical reactions, therapeutic purposes and remote applications (Supplementary material 1.12–1.15).

Here, we have developed a fabrication methodology for paper and CA-based heaters using 'pencil-on-substrate' approach. The fabrication process is simple, fast and involves pencil traces on substrates that yield a heating device. Gravimetric analysis was used to estimate graphite content of the heater and its correlation with base resistance. Even though the fabrication process is rudimentary, temperatures up to 100°C can be easily attained by the paper-based heater. Similarly OHP-based heaters can be used up to 60°C for various applications. This study demonstrates a simple, flexible, cost-effective and portable heater useful in a variety of applications. The use of the device has been successfully demonstrated as a heating source in research and therapeutic domains.

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