Electronic Supplementary Information

Graphite on Paper as Material for Sensitive Thermoresistive Sensors

Toan Dinh,*[a] Hoang-Phuong Phan,[a] Dzung Viet Dao,[a,b] Peter Woodfield,[b] Afzaal Qamar,[a] and Nam-Trung Nguyen [a]

[a] *Queensland Micro-Nanotechnology Centre, Griffith University, Queensland, Australia.*
[b] *School of Engineering, Griffith University, Queensland, Australia.*
* *Email of corresponding author: toan.dinh@griffithuni.edu.au*

(1) Impact of thermal expansion and bending of the paper on the relative resistance change of the GOP

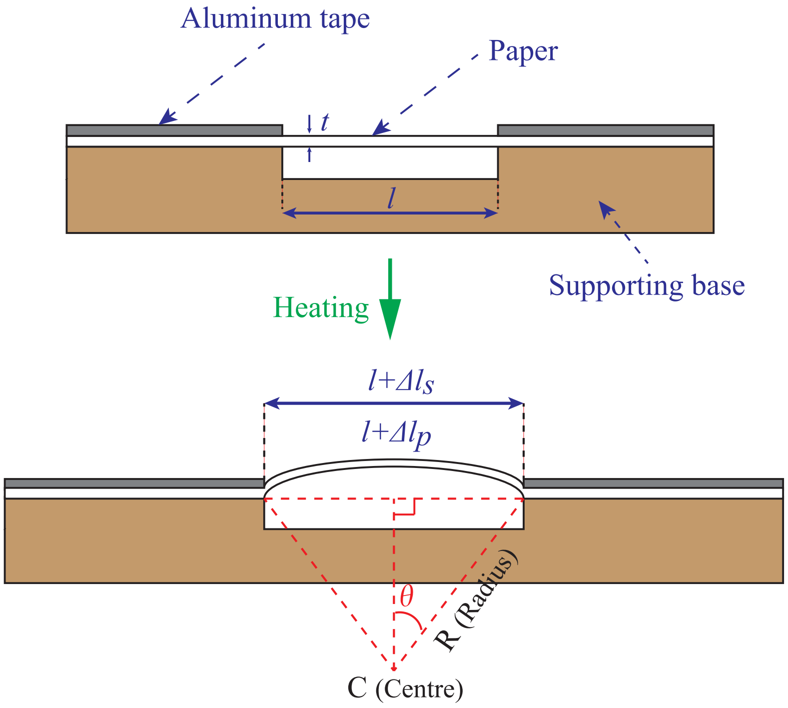

Figure 1: Impact of thermal expansion and bending of the paper on the resistance change of the GOP (not to scale).

Since both the paper and the supporting base can expand with increasing temperature, the influence of the strain effect on the GOP resistance change due to thermal expansion needs to be taken into account. For the purpose of simplicity, we consider a one dimensional thermal expansion model as shown in Fig. 1. The paper is bent upwards with a curve radius of R due to the thermal expansion of the paper. Let l be the initial length of the paper. The additional length of the paper Δl_p and supporting base Δl_s can be calculated using:

$$\Delta l_p = l\alpha_p \Delta T \tag{1}$$

$$\Delta l_s = l\alpha_s \Delta T \tag{2}$$

where ΔT is the temperature change, α_p and α_s are the thermal expansion coefficients of the paper and supporting base, respectively. From Fig. 1, we have the following relationships:

$$l + \Delta l_p = R(2\theta) \tag{3}$$

$$\sin(\theta) = \frac{l + \Delta l_s}{2R} \tag{4}$$

where θ is half the subtending angle (measured in radians). Using the Taylor expansion for $sin(\theta)$, Eq. 4 can be written in the following form:

$$\frac{\theta}{1!} - \frac{\theta^3}{3!} + O\left(\theta^5\right) = \frac{(l + \Delta l_s)\,\theta}{l + \Delta l_p} \tag{5}$$

Since $O(\theta^5)$ is very small in comparison to $\theta/1!$ and $\theta^3/3!$, it can be neglected. Deducing from Eq. 3, 4 and 5, θ and R can be respectively calculated as:

$$\theta = \sqrt{\frac{6(\Delta l_p - \Delta l_s)}{l + \Delta l_p}} \tag{6}$$

$$R = \frac{l + \Delta l_p}{2\theta} \tag{7}$$

The strain ε caused by the paper bending is then approximately estimated using:

$$\varepsilon = \frac{t}{2R} \tag{8}$$

where $t \sim 110\mu m$ is the thickness of the paper. Therefore, the resistance change due to the paper bending is calculated using the following equation:

$$\Delta R/R = GF\frac{t}{2R} \tag{9}$$

where GF is the gauge factor of the pencil type used in this study. The GF value was measured using the bending beam method reported elsewhere[1] to be approximately 10; which agrees with results reported previously[2]. Subsequently, we consider the following cases:

Case 1: When the GOP is only locally heated by the Joule heating effect, and therefore there is no expansion of the supporting base. Based on equations 1, 2, 6, 7 and 9 with the thermal expansion coefficients of the paper[3] $\alpha_p = 15.10^6\ K^{-1}$ and supporting base $\alpha_p = 0$, the relative resistance change of the GOP due to paper bending at 380 K is estimated to be smaller than 1.8 %. This is much smaller than the total resistance change of the GOP (24%). Therefore, the impact of the paper bending on the resistance change can be neglected.

Case 2: When the GOP was heated in the oven, the thermal expansion coefficient of the printed circuit board (PCB) supporting base approximately equals that of the paper[4] ($\alpha_s = 15.10^6\ K^{-1}$). Therefore, paper bending may not occur and only the thermal expansion of the paper affects the resistance change of the GOP. The impact of the paper expansion on the relative resistance change $\Delta R/R$ due to the piezoresistive effect is expressed by:

$$\Delta R/R = GF\alpha_p\Delta T \tag{10}$$

Substituting the values of GF, α_p and ΔT into Eq. 10, the relative change of resistance due to the thermal expansion of the paper is estimated to be 1.2% at 380 K. Consequently, the thermal expansion of the paper has only a small influence on the resistance change.

Therefore, in both cases, the influence of thermal expansion and bending of the paper can be neglected.

(2) Time response of the GOP anemometer

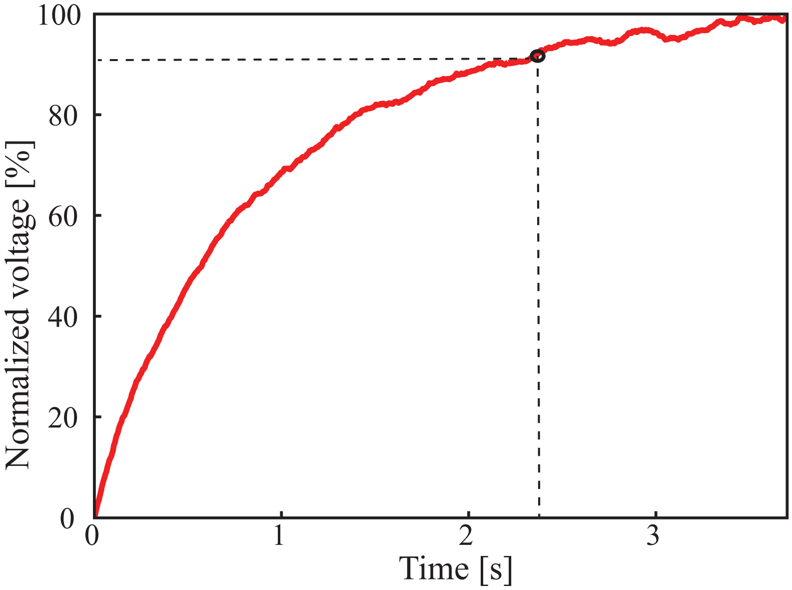

Figure 2: Response time of the GOP-based anemometer.

Figure 2 shows the time response of the GOP anemometer. The rate (%) of the normalized voltage is plotted versus time (s) from the moment that supply of a constant current of 10 mA was started[5,6]. The normalized voltage $\Delta V/V_0$ is calculated using:

$$\Delta V/V_0 = \left|\frac{V - V_0}{V_0}\right| 100\% \tag{11}$$

where V_0 is the output voltages of the GOP at the starting moment. The thermal response of the GOP sensor was measured at room temperature (23 $^\circ C$) in quiescent air and under atmospheric pressure. The 90% response time of the GOP sensor was measured to be approximately 2.3 s. The large sensor size, low thermal conductivity of the paper and clay in the pencil trace can all cause this low response time.

References

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