Research Article

Pencil-on-Paper Capacitors for Hand-Drawn RC Circuits and Capacitive Sensing

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Electronic capacitors were constructed via hand-printing on paper using pencil graphite. Graphite traces were used to draw conductive connections and capacitor plates on opposing sides of a sheet of standard notebook paper. The paper served as the dielectric separating the plates. Capacitance of the devices was generally < 1000 pF and scaled with surface area of the plate electrodes. By combining a pencil-drawn capacitor with an additional resistive pencil trace, an RC low-pass filter was demonstrated. Further utility of the pencil-on-paper devices was demonstrated through description of a capacitive force transducer and reversible chemical sensing. The latter was achieved for water vapor when the hygroscopic cellulose matrix of the paper capacitor's dielectric adsorbed water. The construction and demonstration of pencil-on-paper capacitive elements broadens the scope of paper-based electronic circuits while allowing new opportunities in the rapidly expanding field of paper-based sensors.

1. Introduction

Recently, there has been a resurgence of interest in the use of paper as an inexpensive and environmentally friendly substrate material for electronic circuits and sensors [1, 2]. Transistors, luminescent displays, solar cells, batteries, capacitive touch pads, and super capacitors have all been demonstrated through sophisticated printing and/or coating methods used to deposit various organic or inorganic materials onto the surface of the paper substrate [3–10]. While these efforts certainly demonstrate the scope of what is possible using paper as a canvas for more traditional fabrication methods, other groups have begun using specialty papers or even graphite from pencils as a conductor to draw or connect circuit components. Even resistive sensors have been drawn directly on the paper surface [11–15]. This approach offers the simplicity and low-cost required to extend the realm of paper-based electronics. However, further expansion of draw-on paper electronics requires simple and reliable solutions for construction of discrete circuit components such as resistors, capacitors, transistors, and diodes.

This communication provides a simple route to construction of pencil-on-paper, draw-on capacitors. Parallel-plate

capacitors are formed from two conductive plates separated by a dielectric with capacitance:

$$C = \frac{\epsilon A}{d}, \quad (1)$$

where ϵ is the permittivity of the dielectric, A is the surface area of the conductive plates, and d is the distance separating the plates. Given that pencil graphite is a conductive material and paper is an insulator, a capacitor may be constructed by drawing conductive plates upon opposing sides of a sheet of paper as illustrated within Figure 1.

Given (1), we expect capacitance to scale with the surface area of the graphite plates sketched onto paper of uniform thickness and composition. To investigate, notebook paper was obtained from an Ampad brand notepad, and a Pentaclic brand type B pencil was used to sketch electrodes. This type of pencil is known to have a higher concentration of graphite, and the resultant traces are more conductive when compared with harder pencil graphite blends. Three pencil lead capacitors were constructed for each surface area of 1, 2, 3, 5, and 10 cm² and the devices' capacitance was measured with a Global Specialties Corporation model 3001 capacitance

FIGURE 1: Rendering of pencil-on-paper capacitor. Graphite traces on opposing sides of paper serve as conductive plates and the paper is the capacitors dielectric.

FIGURE 2: Plot of measured capacitance versus surface area of the pencil graphite capacitor plate. Error bars represent standard deviation for replicate capacitors.

meter. A time-lapse video illustrating capacitor preparation is provided in supplementary information available online at <https://doi.org/10.1155/2017/4909327>.

When such devices were constructed, the observed capacitance of devices scaled with the surface area of the paper capacitors plates as demonstrated within Figure 2 and predicted through (1). The capacitance of devices tested was generally < 1000 pF; however, larger values may be expected if the surface area of the paper is increased beyond the devices tested herein.

After initial characterization of the devices capacitance, their electronic and sensing properties were explored further. Figure 3 illustrates a Bode plot (frequency response) of a RC circuit drawn onto notebook paper. For this experiment, the resistive element was a separate pencil trace constructed from 4B pencil graphite, which is more resistive. The resistance arm was approx. 140 k Ω and measured capacitance was approx. 500 pF.

Remarkably, the -3 dB point was within an order of magnitude of the theoretical value of roughly 2600 Hz for this circuit. Deviation from theory may be a result of the capacitors internal resistance.

Figure 4 illustrates how a 12.5 cm² pencil-on-paper capacitor can be used as a force sensor. In this experiment, the

FIGURE 3: Bode plot for pencil-drawn RC filter. The circuit diagram is illustrated in the photograph. Circuit gain was determined by measuring peak-to-peak voltage (V_{pp}) of a sine wave of stated frequency at circuit output for constant magnitude input.

paper capacitor was placed between two sheets of insulating wax paper and a metal spacer was placed onto the assembly. The apparatus was placed upon a flat, hard surface and test masses were placed onto the metal spacer exerting a force upon the paper capacitor. The applied force created mechanical stress within the paper and this leads to compression flattening/stretching of the paper matrix. In agreement with (1) this leads to increased capacitance. Average capacitances scaled with object mass from minimum detectability (50–60 g) to the typical mass of humans. While the capacitive paper sensor did exhibit significant imprecision and hysteresis after large masses were applied, the low-cost of the device may make paper-based force sensors attractive options for certain applications. A video clip demonstrating a capacitive force sensor is provided online in supplementary information.

The final application pursued was use of the capacitive devices for chemical sensing. In this experiment, a 1 cm² pencil-on-paper capacitor was placed within a chamber that was perfused with an airstream for which the relative humidity (RH) could be controlled and monitored with a traceable hygrometer. Given that the cellulose matrix of the paper is hydrophilic, it can adsorb water vapor at elevated humidity, which can change the capacitance of the paper

FIGURE 4: Plot of measured capacitance change versus applied mass for the pencil-on-paper force sensor. Error bars represent 95% confidence intervals. The capacitance noted represents the change in capacitance after tare when no mass was applied.

FIGURE 5: Measured capacitance of a 1 cm^2 pencil-on-paper chemical sensor plotted versus water vapor density. Error bars represent the standard deviation of replicate measurements.

device. Because the changing capacitance can be monitored, the paper capacitor can serve as a chemical sensor. Figure 5 reports capacitance data for a wetting/drying cycle. For this experiment, the capacitor was originally placed within a room temperature (25°C) and very low (0.1%) humidity environment and capacitance values were $< 100\text{ pF}$. Upon increasing the water vapor density, an increase in capacitance was noted as the paper device adsorbed water vapor. Either swelling of the cellulose fibers or variation of the permittivity (or both) is the proposed mechanism for increases in the capacitance.

The increase in capacitance was a nonlinear function of water vapor density with large increases in capacitance above $6\text{ g/m}^3\text{ H}_2\text{O}$ (30–40% RH). During experimentation, it was noted that if the relative humidity exceeded approx. 35–40% the capacitance of the sensor became very unstable. As a result, the water vapor density was kept below this critical humidity during testing. After wetting of the cellulose dielectric, the water vapor density was then lowered by slowly perfusing the chamber with dry air and the capacitance was observed to fall and eventually return to the original levels below 100 pF . However, a hysteresis effect was observed as measured capacitance lagged at higher levels during drying. Such hysteresis in the deliquescence/efflorescence behavior of paper has previously been described [16]. Nonetheless, the results of Figure 5 clearly indicate that the paper capacitor can serve as a chemical sensor. The notebook paper capacitor produced no response to a saturated vapor of hexane, toluene, and acetone. However, a nonsignificant (approx. 1σ) increase in capacitance was observed for a saturated methanol vapor. These results may indicate that hydrogen bonding may be an important chemical factor in producing capacitive response. Previously, resistive humidity sensing on paper matrices has been demonstrated [17].

The use of paper as a dielectric and support for graphite-based electronics remains a promising area of research. Future advancement requires additional functional circuit components be developed. Engineering pencils that etch higher (and variable) conductivity graphite traces would also be a useful research tool. Constructing capacitive sensors from paper that has been chemically modified is a particularly exciting area of future research for sensing applications. Such modifications of the paper may impart chemical selectivity in capacitive measurements using paper as a dielectric.

Conflicts of Interest

No competing financial interests have been declared.

Authors' Contributions

J. Thompson collected and reported data, prepared plots, and authored the manuscript.

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