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Hand-drawn Resistors, Capacitors, Diodes and Circuits for a Pressure Sensor System on Paper.

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Abstract

Hand-written fabrication techniques offer new ways of developing customizable, biodegradable and low-cost electronic systems. In this work, a new level of complexity is demonstrated for hand-written electronics by fabricating passive components, circuits and a sensor system on paper. The system comprises a pencil-written graphite force-sensitive-resistor, a pencil-drawn RC-filter, a pen-written half-wave rectifier, and a commercial front-end voltage amplifier. The sensor system exhibits a linear response for pressures up to 1.2 kPa, and a sensitivity of 51 mV kPa^{-1}. Furthermore, the electrical and mechanical performance of the single components and circuits is studied. Diodes fabricated through pen-written deposition of silver and nickel contacts on amorphous Indium-Gallium-Zinc-Oxide coated paper show rectification ratios up to 1:8. Tensile and compressive bending measurements applied to all pencil-written components for radii down to 0.1 mm indicate minor influence of strain. Similar results are obtained for circuits created from these individual components. Diodes and half-wave rectifiers show a stable behavior when bent to a radius of 5 mm. The presented

techniques can enable the development of flexible and eco-friendly wearables and sensors for consumer and healthcare applications, and are an effective way for school-pupils to explore the world of electronics.

1. Introduction

As electronic systems become embedded into the whole spectrum of human activities, new approaches are required to make customized electronics cheaper and easier to produce. Paper, one of the most ubiquitous materials in history, has already been utilized as substrate and dielectric in devices such as thin film transistors,[1–3] point-of-care sensors,[4,5] or supercapacitors.[6,7] These led to flexible[8], biodegradable[9] and recyclable[10] electronics, but still relied on complex fabrication techniques which generally require vacuum, elevated temperatures and expensive machinery. Due to the natural compatibility between paper substrates and pen/pencil based deposition techniques, hand-drawn layers provides a more immediate approach to deposit and structure materials. In this respect, conductive inks have been developed using solutions containing silver,[11] metallic nanowires,[12] indium-gallium alloys[13] or carbon nanotubes.[14] In addition, inks containing semiconductors such as zinc-oxide[15] or poly-3-octylthiophene[16] have been developed. These materials have been used for the development of electrocardiogram sensors,[17] antennas,[18] displays,[19] and transistors.[20–22] Nevertheless, the complex synthesis required to produce such inks limits their widespread use. Graphite, on the other hand, is an abundant and cheap material, and lead pencils have been used to write on paper since the 16th century.[23] More importantly, due to the bulk structure of graphite, which consists of disorganized clusters of stacked graphene sheets connected by Van der Wall bonds, graphite is an electrically conductive material. Hence, commercially available pencils can be used to fabricate pencil-written electronic components, circuits, and sensors.[24–28] In this work, the complexity and functionality of hand-written electronics is moved to a new level through the development of a complete pressure sensor system which also features the first hand-written Schottky diode on paper. The presented system is based on a pen and pencil-written half-wave rectifier, as well as a low-pass filter and percolation force sensitive resistor. It also includes an off-the-shelf operational amplifier biased using hand-written passive components. The amplifier acts as a sensor conditioning circuit and improves the signal-to-noise ratio of the device. The realization of the system relied on a detailed characterization of the discrete components to evaluate and define the fabrication parameters.

Pencils containing different graphite-to-clay ratios allow for the fabrication of thin-film resistors with varied sheet resistances. Changing resistance values is easily achieved by either removing or adding graphite layers to or from the existing structures, making the prototyping process faster. Graphite-paper-graphite parallel plate capacitors demonstrate capacitance values as high as 141 pF cm^{-2}; this is three times larger than similar existing paper capacitors.[29] Larger capacitances can only be reached utilizing high-k solutions such as sulfuric acid.[30] Hand-written Schottky diodes on paper exhibiting rectification ratios of 1:8 were also fabricated and studied. All hand-written devices are used to realize circuits including rectifiers and filters for frequencies up to 13.56 MHz. Finally, all presented devices and circuits were tested under tensile and compressive stress. Bending radii down to 100 µm, (corresponding to complete folding and strain of 50 %) were applied while the devices remained fully functional. The results demonstrate the potential of the presented technique for the development of complex, flexible hand-written electronic systems, broadening the scope of inexpensive, eco-friendly and readily available electronics.

2. Results and Discussion

2.1. Pressure Sensor System

The potential of the presented hand-written electronics is demonstrated through the fabrication of a fully integrated pressure sensor system (**Figure 1**a). The output signal of this system exhibits a linear behavior for applied pressures between 0.2 kPa and 1.2 kPa, with a sensitivity of 51 mV kPa^{-1}. This is comparable to other percolation and strain based flexible pressure sensors, with the added advantage of a simple and inexpensive fabrication process (Figure 1b).[31] Liao et al.[32] developed a highly sensitive graphite strain sensor with a gauge factor of 536.6, nevertheless, the conversion of strain to pressure is complicated due to variables such as dimension of the device and elastic modulus of the paper substrate. Liana et al.[33] fabricated a strain sensor that featured an optical readout system which required a mixture of copper particles, polydimethylsiloxane and carbon paste to operate. In comparison, the techniques demonstrated here can be used to develop pencil/pen-written biodegradable electronic scales, accelerometers and resistive touch user interfaces in a straightforward manner, with key applications in fast device prototyping, as well as in teaching environments where commercial electronic development tools are too costly. **Supplementary Video S1** demonstrates a hand-written MIDI keyboard, showcasing the versatility and simplicity of this technique. The structure layout for the pressure sensor system is shown in Figure 1c and the circuit schematic is presented in Figure 1d. The system is constituted by three sub-systems: rectification and high-pass filtering to remove the negative component of the AC input signal and the high frequency background noise (Figure 1e); this is followed by the modulation of the signal's amplitude in a voltage divider made from a pencil-written 21 kΩ resistor and the force sensing resistor (FSR) (Figure 1f); lastly, the sensor's output signal is amplified (Figure 1g) to recover the signal from attention caused by the first two stages. Two hand-drawn graphite resistors of 4 kΩ and 40 kΩ provide a voltage gain of 11 when used in a non-inverting configuration with the off-the-shelf operational amplifier. The FSR consists of two stacked graphite contacts separated by a ring-shaped paper spacer. The bottom contact is fabricated by drawing two interdigitated graphite tracks; these graphite tracks are separated by a 2 mm gap to ensure that no resistive contact exists between the two sections when no pressure is applied. The top contact consists of a drawn graphite filled circle which bridges both bottom contacts when pressure is applied. In contrast to strain sensors, where the resistance variation originates from the bending of a resistive film, the resistance variation in percolation FSR originates from the increase in conductivity as both the top and bottom layers are pushed together, and the contact area between different graphite clusters increases (Figure 1f). The sensor system was tested by measuring the averaged output signal for various applied pressures, as shown in Figure 1a. The half-wave rectifier simplifies the readout process by eliminating the negative peaks of the sensor output. The small error obtained (< ±12 %), combined with the obtained linearity and sensitivity showcase the capabilities of the presented techniques.

In addition to the pressure sensor system, other modalities such as humidity, strain and temperature can be detected using this technology. The latter is demonstrated in supplementary **Figure S1**. A pencil-written temperature sensor exhibits a linear behavior in temperature ranges from 50℃ to 140℃, with a sensitivity of -7.7×10^{-4} $(\Omega/\Omega_0)/℃$.

2.2. Single Components

Figure 2a presents the layout of the three basic hand-written electronic devices used to realize the described sensor system. Figure 2b shows the relation between conductance and width to length (W/L) ratio for resistors fabricated with two different types of commercial pencils (graphite contents of 92.5 ± 2.5 % and 72.5 ± 2.5 %). The sheet resistance of the resistors fabricated through this technique was evaluated using a set of 30 devices for both pencil types. Resistors made from pencils with higher graphite-to-clay ratio exhibited a sheet resistance of 500 ± 31 Ω□, while an average value of 7.7 ± 0.4 kΩ□ was obtained for the resistors fabricated using the lower graphite-to-clay ratio pencils. Given their superior reliability and conductivity, higher graphite content pencils are preferable for the fabrication of electronic devices. In addition, the current-to-voltage characteristics of resistors with different W/L ratios demonstrates their linearity (Figure 2c). The simplicity and reliability of the tuning process is shown in **Video S2**, where the precise adjustment of the resistance was achieved by removing graphite layers with a pencil eraser, or by depositing additional graphite layers.

The parallel plate capacitors were fabricated using high graphite content pencils (92.5 %) with two distinct contact types, namely compact and sparse. These classifications relate to the density of the graphite films. Sparse film deposition was performed by dragging the pencil on the paper once, whereas compact graphite films were the result of 10 repeated depositions to ensure a continuous layer – **Figure S2a and b** show that the sparse layers cover only 45 % of the paper area, which leads to highly resistive contacts (> 1 MΩ). Figure 2d presents the specific capacitance extracted from a total of 50 samples. The average specific capacitance for compact graphite capacitors is 117 ± 4 pF cm^{-2}, and sparse graphite capacitors exhibit a value of 20 ± 5 pF cm^{-2}. Furthermore, the frequency dependency of compact capacitors is not significant for frequencies from 1 kHz to 10 MHz. In contrast, sparse graphite capacitors exhibit a drop of capacitance by two orders of magnitude in the same frequency interval

(**Figure S3**). This decrease in capacitance is explained by the parasitic resistance of the structures. This parasitic resistance, in combination with the capacitance, creates a low-pass filter that attenuates high frequency signals.

The last component required for the fabrication of the sensor system is a diode. Diodes were manufactured by deposition of Ag and Ni contacts on a-IGZO coated paper using conductive ink pens. Optical imaging of both coated and uncoated area is shown in Supplementary Figure S2d, while insets e, f, g and h show AFM micrographs of the substrate. Figure 2e shows the IV characteristics of an Ag-Ni diode fabricated on paper before and after annealing. The device exhibits a turn-on voltage of 0.6 V and a rectification ratio of 1:8. Without annealing, the fabricated diodes have an almost ohmic behavior. Nevertheless, as shown in Figure 2f, annealing at 150℃ for 10 min under ambient conditions results in an increase of the current rectification ratio from 1:1.25 to 1:4.5 for forward and reverse bias voltages of +1 V and -1 V. Annealing for an additional period of 60 min led to a further increase of the rectification ratio to 1:8. At the same time, the maximum ON current decreases after the 60 min annealing step. Previously, the formation of AgO_x at the interface of silver and a-IGZO has been correlated with the formation of a Schottky barrier, as the mismatch in the work function of a-IGZO (4.5 eV) and silver (4.26 eV-4.74 eV) is not enough to explain this effect. The measurements indicate that longer annealing times increase the thickness of interfacial non-conductive AgO_x, and improve the rectification ratio.[34] a-IGZO was chosen as it can be deposited at room temperature, and remains operational when bent to radii down to 25 µm. Furthermore, a-IGZO is a common semiconductor material used for development of flexible analog electronic systems.[35,36] For instance, a-IGZO has been employed in the fabrication of flexible Schottky diodes using vacuum based manufacturing techniques. These demonstrated high-frequency operation (2.45 GHz)[37] and rectification ratios up to 10^7.[38]

2.3.Pen/pencil-written circuits

The presented single components are suitable for the development of a variety of circuits. To characterize the sub-systems of the pressure sensor system, individual low, high and band-pass filters, as well as a half-wave rectifier, were fabricated. **Figure 3**a shows 1st order low and high pass filters on paper. These filters were fabricated by drawing a resistor and a capacitor in series. Figures 3b and 3c, show the frequency response for two low-pass filters with -3 dB cut-off frequencies of 3 kHz and 60 kHz. Figures 3d and 3e show the response of two corresponding high-pass filters exhibiting cut-off frequencies of 7 kHz and 60 kHz. These filters present the typical behavior of low and high pass filters, and exhibit a signal attenuation of ≈15 dB/dec beyond the cut-off frequency. By adding or removing graphite layers to/from the resistors, the RC time constant of the filters can be tuned, enabling accurate control of the cut-off frequency. Following the fabrication of single pole filters, a band-pass filter for 13.56 MHz aimed for RFID applications was developed (Figure 3f). This circuit was designed to be compatible with applications such as electronic ticketing and garment tracking, as inexpensive and biodegradable circuits are desirable for both applications.

The output signal of a half-wave rectifier consisting of a pen-written diode and pencil-written resistor is shown in **Supplementary Figure S4**. The attenuation of the input signal by a factor of 11 is caused by the 70 kΩ output resistor. This value is smaller than the diode’s forward resistance of 750 kΩ at 5 V bias voltage.

In addition to the fabrication of hand-written electronic devices, the possibility of using paper as a carrier substrate for off-the-shelf components was evaluated. Here, a customized printed circuit board (PCB) was fabricated to interface and to bias a voltage amplifier (Figure 3g). A commercially available off-the-shelf operational amplifier was fixed to a sheet of paper using a Ni pen. The Ni acted as adhesive and Ohmic contact between the amplifier and the pencil/pen written components. The design of this system can be found in **Figure S5**. Using the non-inverting configuration shown in Figure 3h, two graphite resistors, of 3.1 kΩ and 362 Ω, were used to define the voltage gain of the amplifier circuit. As shown in Figure 3i, this amplifier exhibits a gain of 19.5 dB and a – 3 dB cut-off frequency of 30 kHz. This device can thus be implemented to condition the output signal of a variety of sensor systems. It also demonstrates the potential of paper PCBs to be used as an alternative substrate to conventional fiber glass circuit boards. Such fabrication process is ideal for disposable or prototyping applications, as it does not require specialized and often costly equipment such as PCB milling machines or etching.

2.4. Bending stress

Typically, flexible devices suffer from strain related effects. Due to this, the behavior of all the electronic components and circuits was tested for various bending radii, ranging from 5 mm to 100 µm. The results indicate that resistors exhibit almost no variation in their resistance for tensile and compressive bending down to 0.1 mm, equivalent to strain of 50 % (**Figure 4**a). The strain was calculated using an equation adapted from previous reports on thin-film bending.[39,40] These bending radius corresponds to complete folding. While re-flattening after tensile folding has minor effects, re-flattening after compressive folding results in a resistance increase of two orders of magnitude. This is because tensile cracks created by the extension of graphite, allows for both edges of the crack to come into contact after re-flattening. Contrarily, compressive cracks are generated by the formation of excess material across the folding line, which delaminates from the surface. In the case of capacitors (Figure 4b), as the graphite electrodes were drawn on both sides of the paper, no difference exists between tensile and compressive bending. Capacitors with compact graphite contacts show a stable performance for all bending radii. In contrast, the sparse capacitors demonstrated a decrease of 25 % of the capacitance when re-flattened after undergoing complete folding. To characterize the stability of the diodes, a bending radius of 5 mm (1 % strain) was applied and their IV curves were studied (Figure 4c). The On current of the diodes was found to decrease by 23 % during the bending cycle, which is explained by the low adhesion of the nickel and silver contacts to the a-IGZO coated paper, resulting in the delamination of the metal layers. Nevertheless, when re-flattened, the On current increased to 83 % of its original value. For bending radii below 5 mm, the a-IGZO diodes cease to function. The rectification ratio remained constant after the device had been bent and re-flattened. As shown in **Figure S6**, the AC response of a half-wave rectifier bent to a radius of 5 mm followed the DC behavior of single diodes. The maximum output signal dropped by 18 %, followed by a recovery to 91 % of the input signal after re-flattening. The low and high pass filters did not show any performance variation when undergoing bending (1 % strain), and did not suffer from long-term variations after being re-flattened; mirroring the behavior of the individual components (Figure 4d,e). The strain applied to these devices should never surpassed 1 % as a loss of function is observed otherwise. The band-pass filter transmission level decreased from 6 dB to 10 dB when re-flattened after undergoing bending to a radius of 5 mm (1 % strain), but did not show any shift in the cut-off frequencies (Figure 4f). The results reported, validate the fabricated hand-written components and circuits for the implementation in flexible electronics.

3. Conclusion

In this work, pencils and conductive pens were used to fabricate a pressure sensor system on paper. The complete pressure sensor system exhibits a linear behavior for pressures up to 1.2 kPa and a sensitivity of 51 mV kPa^{-1}. The techniques used to fabricate this system demonstrate the possibility to develop devices such as biodegradable tags, biometric sensors, and novel flexible human machine interface systems. Additionally, the fabrication of the first hand-written Schottky diode and half-wave rectifier was reported. A maximum rectification ratio of 1:8 was obtained for the presented Ag/a-IGZO/Ni hand-written diodes, a value that remained constant even when the devices were subjected to a strain of 1 % and subsequently re-flattened. The rectifying properties of these devices were shown to be related to temperature treatment and AgO_x formation at the interface. The behavior of all devices and circuits was studied under bending. Resistors, capacitors and RC filters showed no significant performance variation when bent down to radii of 100 µm. The presented work demonstrated the versatility of using commonly available materials and writing tools for the fabrication of circuits on paper substrates. Considering the advantages of hand-written electronics, and the electrical and mechanical performances achieved, this work is a major step towards the development of more complex hand-written circuits as a flexible and eco-friendly alternative to standard electronics.

4. Experimental Section

4.1. Single Components

Standard printer paper with a thickness of 100 µm was used as a substrate for the fabrication of all devices and circuits. B9 (92.5 ± 2.5 % graphite content) and HB (72.5 ± 2.5 %) commercially available pencils from Faber-Castell® were used for the deposition of graphite films. Nickel and silver deposition was achieved using Circuitworks® Nickel Conductive CW2000 and Conductive Micro Tip CW2200 pens from Chemtronics®, respectively. Amorphous Indium-Gallium-Zinc-Oxide (In:Ga:Zn = 1:1:1) was deposited through standard room temperature RF sputtering.[41] Diodes were fabricated on 1 cm^2 to 4 cm^2 a-IGZO coated paper samples using silver and nickel metal inks. The annealing of these devices was performed on a hotplate under ambient conditions. The annealing temperature was 150℃.

4.2. Pressure Sensor System

The pressure sensor system was fabricated on a 100 cm^2 paper substrate. The rectifying stage of this circuit consisted of a diode connected in series with a parallel combination of a resistor and capacitor. The diode was fabricated through the deposition of two 2 mm × 6 mm parallel Ag and Ni contacts on a 1 cm × 1.5 cm a-IGZO coated paper, which was fixed to the main substrate using commercial tape. The Ag terminal of the diode was directly connected to the input of the system. The Ni terminal was connected to the low pass filter made from a 46 kΩ hand-written resistor and a 550 pF hand-drawn capacitor (both 1.5 cm × 5 cm). Both devices were fabricated using a 92.5 % graphite content pencil and a compact graphite profile. The output of this resistor was inputted to the FSR.

The fabrication of the graphite force sensitive resistor followed a 3 layer design. The bottom layer consisted of two asymmetrical groups of graphite tracks, designed to create an interdigitated structure where no contact existed between the two contacts. This structure was fabricated using a B9 (92.5 % graphite content) pencil and exhibited an Off resistance of

23 MΩ. A paper layer was used as a spacer between the bottom and top contacts. This spacer layer determined the sensor's active area. In this case, a 6 cm ×5 cm sheet of paper with a 4 cm diameter hole, corresponding to a total active area of 12.6 cm^2, was fabricated. The top contact was fabricated using a B9 pencil to deposit a continuous graphite layer. The output consisted of a 0.7 cm × 3 cm 21 kΩ resistor fabricated using a 92.5 % graphite content pencil. Finally, the signal was amplified using an OP177 connected in a non-inverting configuration to two resistors of 0.5 cm × 1.6 cm (40 kΩ after being tuned) and 0.6 cm × 1 cm (4 kΩ). Copper tape was used on all devices to improve the contact between circuits and the instrumentation.

4.3. Pen/pencil-written circuits

Low and high pass filters were fabricated through the hand-written deposition of a resistor and a capacitor in series using a B9 type pencil. The components were connected using low resistive Ni ink. The band-pass filter was fabricated by connecting a low-pass filter and a high-pass filter. The employed 480 pF capacitors were fabricated by depositing compact graphite films on opposite sides of the paper substrate using 92.5 % graphite content pencils.

4.4. Bending stress

Bending measurements were carried out in ambient conditions. All samples were bent using stainless steel rods with radii between 5 mm and 0.5 mm. Complete folding of the paper was achieved manually. The resistors, capacitors, and RC filters were bent perpendicularly to the current direction. The diodes and half-wave rectifiers were bent parallel to the diode's channel. The samples were fixed to the stainless-steel rods using standard adhesive without influencing the bending radii.

4.5. Characterization

All AC signals were generated using a Philips PM5139 function generator. AC signals were measured using a Rhode & Schwarz RTM2032 Oscilloscope. Resistances were measured using a 117 True RMS Multimeter from Fluke, whereas capacitances were measured using an

HP4274A multi-frequency LCR meter. The diodes' current to voltage response before and after annealing was characterized using a Keysight B1500A parameter analyser.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Figures

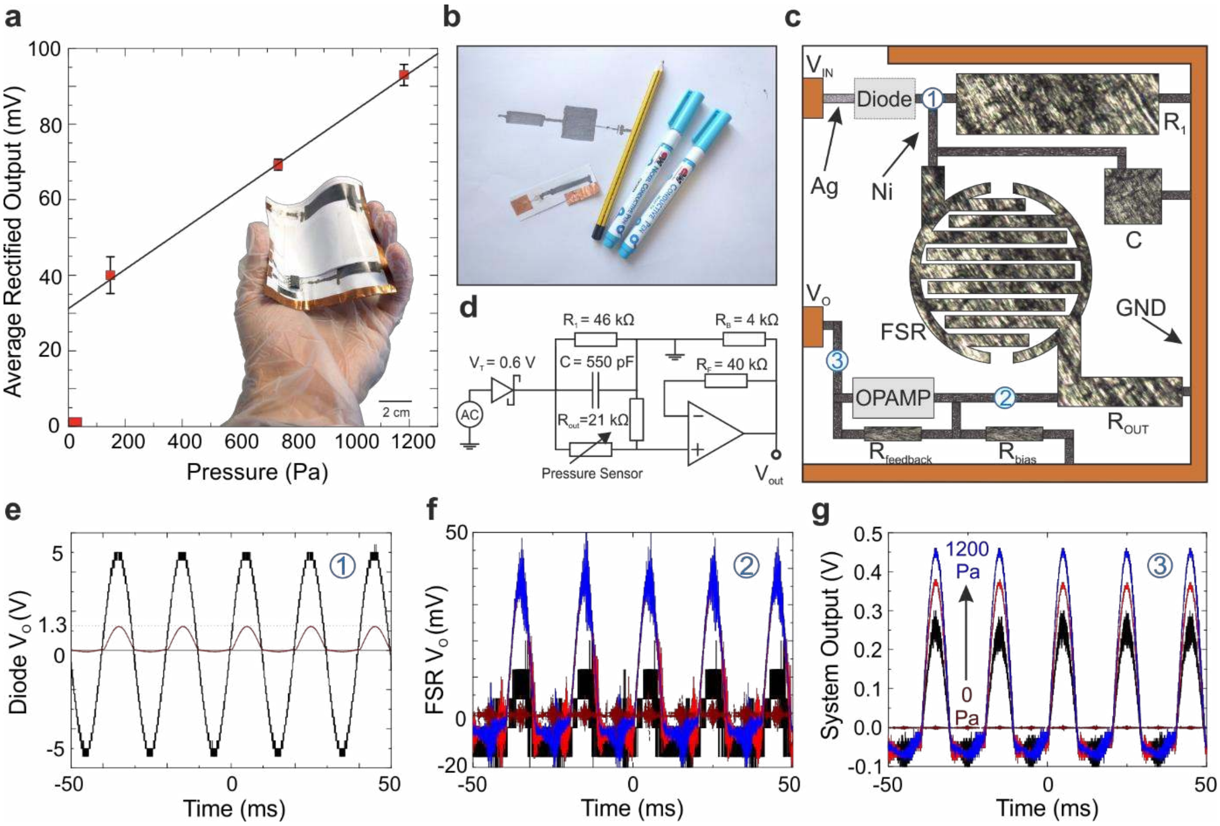

Figure 1 – Pressure sensor system. a) Output signal of an integrated pressure sensor system fabricated on paper. This system presents a sensitivity of 51 mV kPa^{-1} for pressures up to 1.2 kPa. b) Pencil and pen-written devices on a paper substrate. The simplicity of this technique facilitates the development of electronic prototypes. c) Full design of the pressure sensor. This device used a pen-written half-wave rectifier to eliminate the negative component of a 10 V peak-to-peak AC signal, which was then modulated by the pressure applied to a pencil-written force sensitive resistor (FSR). The FSR is integrated into a voltage divider and its output signal is amplified using an off-the-shelf amplifier whose gain of 11 was defined by two hand-written resistors. d) Full circuit schematic of the system, including values of all elements. Intermediate signals from the half-wave rectifier (e), pressure sensing voltage divider (f) and amplifier (g).

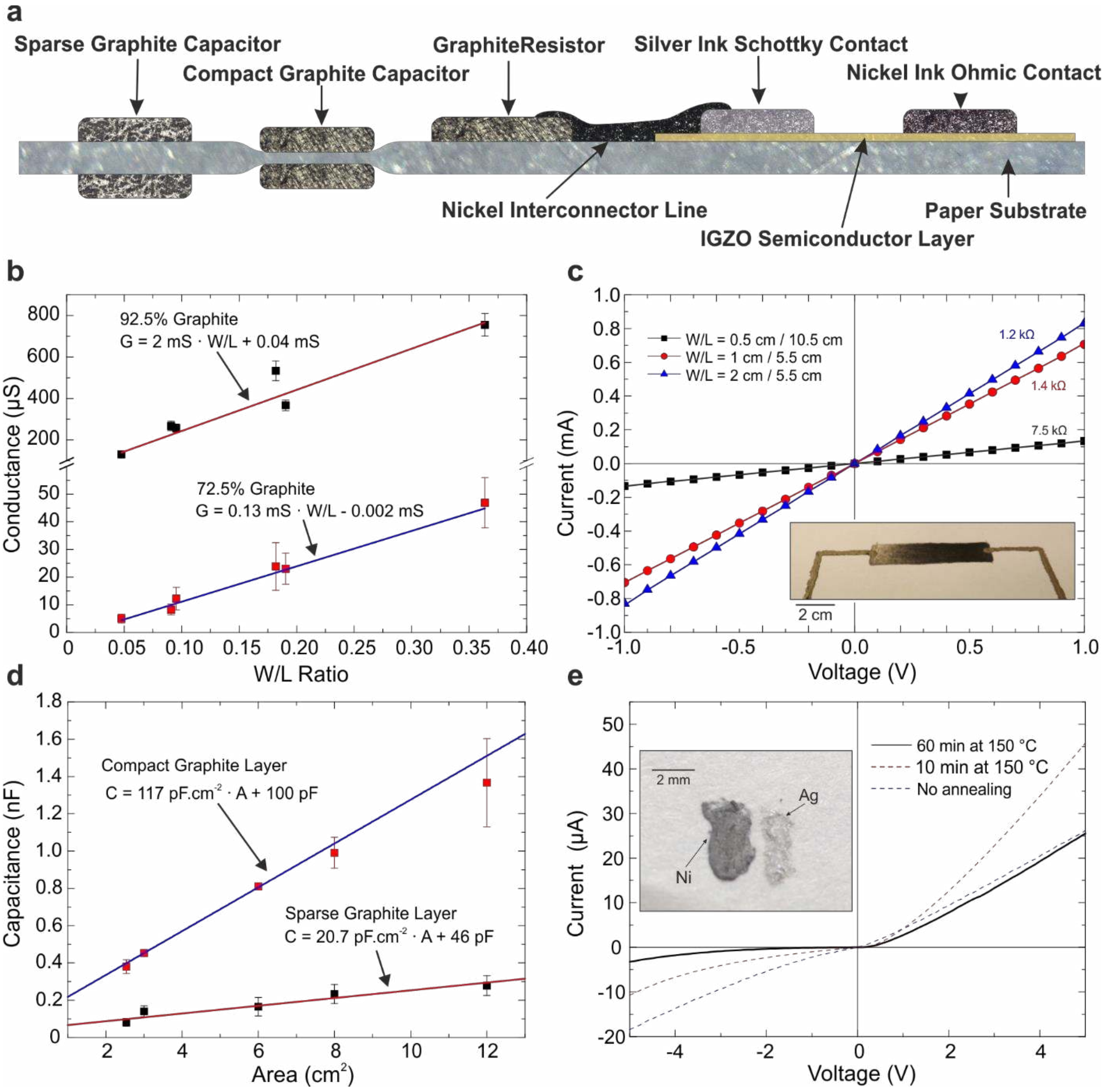

Figure 2 – Hand written single components. a) Layout of the main components. Graphite films were drawn using 92.5 ±2.5 % and 72.5 ±2.5 % graphite content pencils. Ohmic contacts between different structures were achieved through pen-written Ni tracks. Silver and nickel metallic inks were used to deposit Schottky and Ohmic contacts on a paper substrate coated with amorphous Indium-Gallium-Zinc-Oxide (a-IGZO). b) Conductance as a function of the width to length ratio of graphite resistors fabricated using pencils with graphite contents of 92.5 % (30 samples) and 72.5 % (30 samples). The specific conductance value for high and low graphite-to-clay ratio resistors is 500 ±31 Ω□, and 7.7 ±0.4 kΩ□, respectively. c) IV

measurements for three different W/L ratio resistors. The linear behavior indicates an Ohmic contact between nickel and graphite. d) Capacitance of capacitors manufactured from sparse and compact graphite layers. e) IV curve of a Schottky diode fabricated through pen-written Ag and Ni contacts on a-IGZO coated paper. The turn on voltage is 0.6 V. The increase of the rectification ratio after annealing is attributed to the formation of AgO_x at the interface between Ag and a-IGZO.

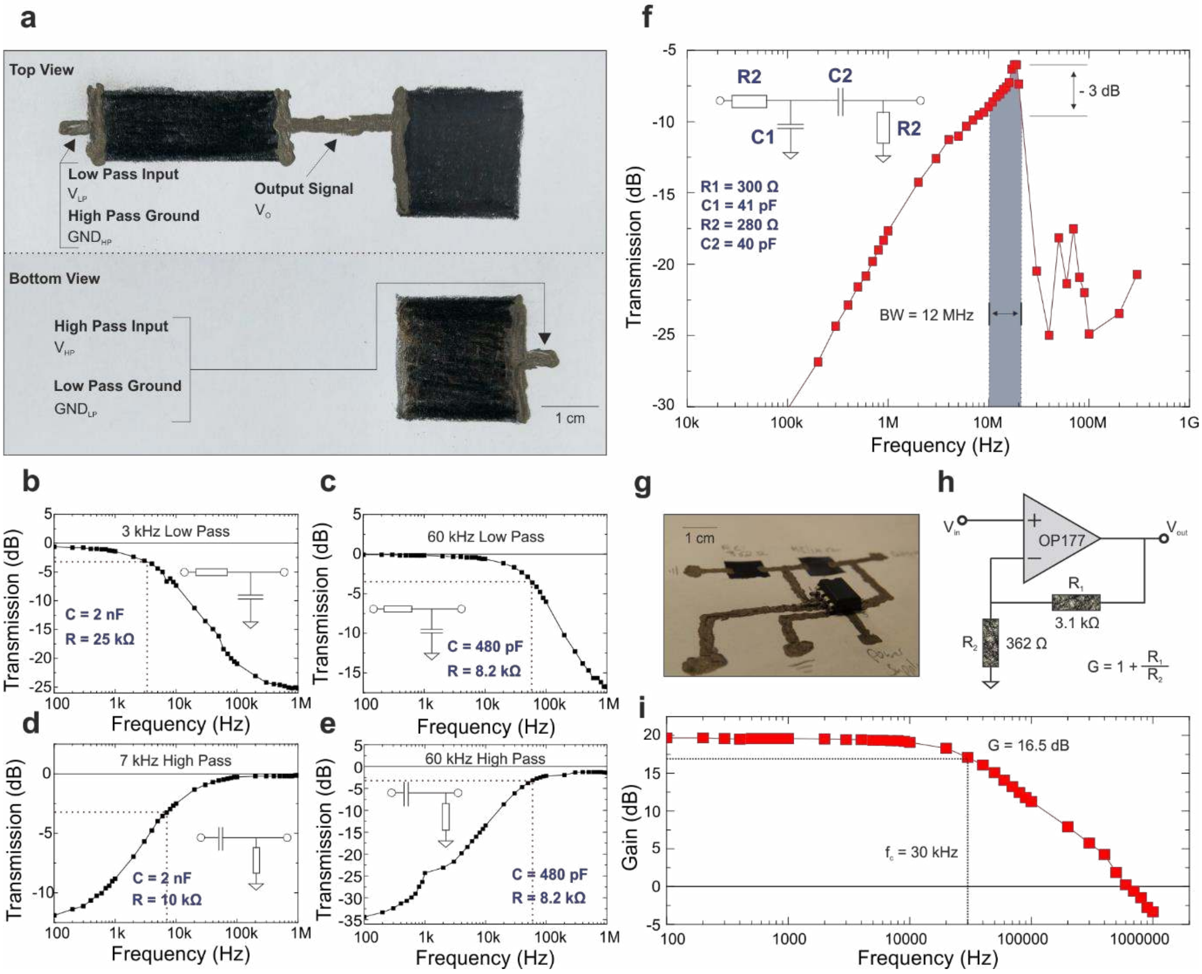

Figure 3 – Hand-written circuits. a) Layout of frequency filters. These devices were developed using graphite and Ni conductive pens. The Top view shows a resistor and one contact of a capacitor, the bottom view shows the opposite side of the paper substrate and hence the second contact of the capacitor. b) and c) 3 kHz and 60 kHz low pass filters. d) and e) 7 kHz and 60 kHz high pass filters. f) 13.56 MHz band pass filter. The blue area indicates the bandwidth of the device (12 MHz). g) Integration of the rigid amplifier on the paper substrate. The amplifier circuit is fixed on paper using the Ni metal ink. h) Schematic of the circuit. This circuit consisted of two resistors of 3.1 kΩ and 362 Ω that connected to the amplifier in a non-inverting configuration. i) Bode plot for this system showing a cut-off frequency of 30 kHz and a gain of 16.5 dB.

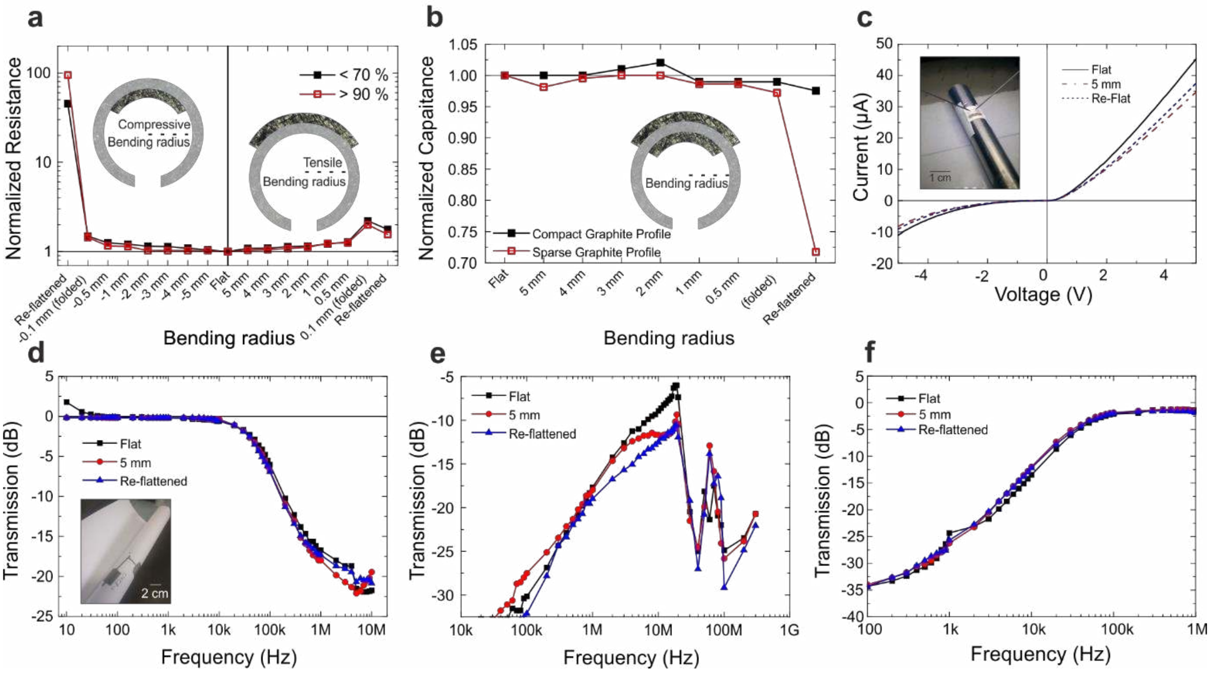

Figure 4 – Hand-written components and circuits under bending stress. a) Variation of the normalized resistance of resistors down to radii of 0.1 mm (complete folding), and subsequent re-flattening. b) Response of hand-written capacitors to bending. c) IV characteristic of a hand-written Ag/a-IGZO/Ni Schottky diode measure while flat bend to a radius of 5 mm and re-flattened. The On current of the device decreases by 23 % when bent, but recovered to 83 % of the initial value after re-flattening. Since the Off current behaves similar, the rectification ratio remained nearly constant. Low (d), band (e) and high (f) pass filters tested under the same bending conditions as the diodes. Both the low and the high pass filters show no performance variation. The band-pass filter shows a decrease in the transmission of the input signal of -4 dB while the cutoff frequencies stay constant.

An integrated pressure sensor system on paper is fabricated using hand-drawn graphite and metal inks, and exhibits a sensitivity of 51 mV kPa^{-1} for pressures up to 1.2 kPa. The system combines different devices including diodes, capacitors and resistors. The latter remained functional even when folded (bending radius 100 µm). This technology represents a promising alternative for customizable, biodegradable and cheap electronics.

Keyword: Hand-written Electronics

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Hand-drawn Resistors, Capacitors, Diodes and Circuits for a Pressure Sensor System on Paper.