Low-Cost Printed RC Filter with Materials from Daily-Life

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Contents

1 Introduction

Electronic devices are constantly being improved and innovated; they have changed our society in so many unimaginable ways and have continued to thrive for nearly two centuries. Today, electronics are driven by high-power technology and require expensive and time consuming processes for their manufacture. Frequently, this demands for the unsustainable extraction of high-priced materials such as arsenic and platinum, through environmentally damaging practices, for instance mining and heating with carbon. There is a great need for low-cost and greener electronics.

Low-cost electronics are progressing using easier techniques such as printing and incorporating flexible and inexpensive materials such as plastics [1]. electronic tattoo sensors [2], organic field-effect transistors [3], electronic biosensors [4] and printing of metal ink for conductors [5] have been developed, employing low-cost methods or materials, including organic substances.

RC filters have applications in radio tuning, ECGs (echocardiograms), and tone controls on electric guitars. These filters can be made with simple passive components – meaning that they are not powered by an external power source – which include a resistor (R) and capacitor (C) (illustrated in Figure 1). The elements of the RC filter work together to block and let through certain frequencies of an electrical signal [6]. Most common filters include low-pass filters and high-pass filters, the distinct difference between the two filters is the position of the resistor and capacitor relative to each other in the circuit. In a low-pass filter, the resistor comes before the capacitor. This is the opposite for the high-pass filter. RC filters have a boundary at which frequencies below or above, depending on the type of filter (low- or high-pass), would be attenuated. This is known as cut-off frequency.

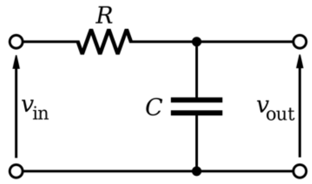


Figure 1: Circuit diagram of a low-pass RC filter

The overall aim of the project was to design and fabricate a low-cost low-pass RC (Resistor-Capacitor) filter using daily household items, while implementing versatile and easy processes. This could in turn relieve the strain modern day technology has on both the environment and the economy. The greener and cheaper electronic could benefit others, especially those in less economically developed countries where more expensive materials are not as readily available. The materials used in electronics, such as gold, could be replaced, making common technology accessible to a wider range of people. With success, this filter could be printed at home, and could inspire the design of more cost-effective electronics. A major part of the aim is to develop a working capacitor using egg white and conductive ink. In order to achieve the aim, the layout of the circuit must be designed, including the arrangement and shapes of the passive components. Research into suitable and preferably green materials or substances must be conducted to produce a functioning and efficient filter. The circuit would be printed using an inkjet printer, or more economically, screen printing to piece each layer and component together and the final model would be connected to an electrical signal to test the filtering effect of the filter.

SATRO Project Plan

The first two weeks of the SATRO summer research placement was heavily research based. This included background research of the electronic science in the project, materials and methods we could potentially use, and reading reports and tests previously completed. The research would help me understand our objectives, and decide on a more appropriate and efficient approach to the project. The remaining three weeks would be focused on experimenting and fabricating, with the last week collecting the results and conducting separate tests on the final products. I had used both printing techniques to fabricate the filters: inkjet printing and screen printing, since these methods are relatively inexpensive, are quick and do not require specialist and complex machinery. The main conductive substance the project would incorporate would be carbon, due to its high abundance and low-cost. My project was especially focused on screen printing the RC circuits, and using carbon-based substances, whilst my research partner was focussing on inkjet printing ink containing silver nanoparticles.

2 Literature Review

2.1 Carbon

Carbon is a naturally occurring, non-metallic element and is the 10th most abundant element in the Earth's crust with a percentage abundance of 0.18% [7]. Most commonly, we use carbon in pencil lead (graphite) and in jewellery (diamond) – both are allotropes of carbon, meaning that they exist as different physical forms of the same element. Another allotrope of carbon is Buckminster fullerene, which is made up of carbon atoms arranged in the shape of a ball or tubes. An electronic application of fullerene tubes are nanotubes shown in Figure 2a, which possess characteristics that make them effective semiconductors.

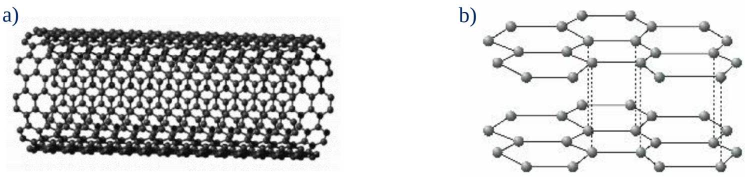


Figure 2: a) Carbon fullerene tubes, b) Structure of graphite

Carbon itself cannot conduct electricity, however, graphite, an allotrope of carbon, can. Its crystalline structure, illustrated in Figure 2b, consists of layers of carbon atoms. Each carbon atom has four unpaired electrons in its outer shell, so can form four bonds [8]. Yet in graphite, each carbon atom is covalently bonded (when atoms share pairs of electrons it forms a covalent bond) to three other neighbouring atoms, and the fourth electron is delocalised between the layers of graphite. Every single graphite layer is attracted to another by weak van der Waals forces; the delocalised electrons move among the layers, inducing opposite dipoles in the sheets. Graphite is able to conduct electricity due to these freely moving electrons that can carry charge.

2.2 Piezo-Electric Inkjet Printing

Piezoelectricity is electric charge that is generated in certain materials that possess the ability to allow the flow of electricity through their structure when mechanical stress is applied [9]. In reverse, when electricity is passed through the crystal, the structure contracts by vibrating from side to side. Typically, the charges in a piezoelectric crystal are electrically balanced. When the structure is deformed through mechanical stress, atoms are forced closer or further apart, and the charges in the crystal become unbalanced, inducing a net electrical charge (shown in Figure 3a). Positive and negative net charges are generated on the exterior surface of the piezoelectric crystal, and therefore produces an electric charge. Inversely, when a voltage is applied across the crystal, the charges within become destabilised, and in order to return to a rebalanced state, the atoms need to move closer or further together, deforming the shape of the crystal through compressions and tensions.

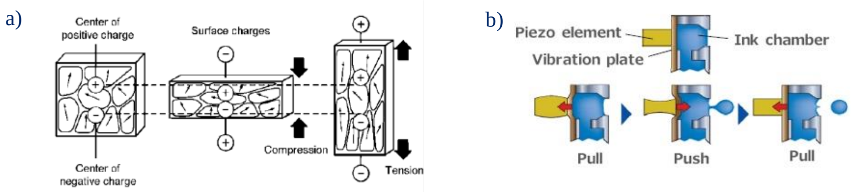


Figure 3: a) Deformation of piezoelectric crystal, b) Typical push-pull mechanism in a piezoelectric inkjet printer

The printer head consists of a piezo crystal which contracts when a voltage is applied, joined to a vibration plate. As the plate flexes with each contraction, the ink stored in the ink chamber is forced through the nozzle in a push pull motion demonstrated in Figure 3b, transferring small droplets of ink at a high speed [10].

2.3 Screen Printing

Screen printing is a versatile and economical printing method, commonly used to transfer ink onto the surface of t-shirts. The graphic is transferred by squeezing ink through a mesh screen onto a substrate, which is divided by a stencil [11]. There are sections of the stencil that are permeable and allow the ink to pass through. The ink adheres onto the surface of the substrate and further layers of ink can be applied to increase its opacity, or to combine colours to graphics.

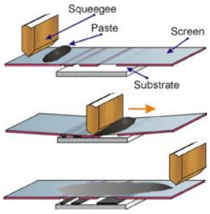


Figure 4: Screen printing process

2.4 Low-Pass Filters

A low-pass filter is an RC circuit that can attenuate frequencies higher than a cut-off frequency and allow frequencies between 0Hz and the cut-off frequency of an electrical signal to pass [12]. A simple low-pass filter can be made with passive circuit components: a resistor (R) placed before the capacitor (C) in series, powered by a voltage. Passive means that the elements of the circuit are not powered by an external power source. At cut-off frequency, which is calculated using the equation in Equation 1, frequencies above this number will be removed, leaving only lower frequencies to pass. The low-pass filter is theoretically ineffective with frequencies lower than the cut-off. Applications of low-pass filters include telephone systems to convert audio signals to certain frequencies and in ECGs in medical practice.

$$f_c = \frac{1}{2\pi RC}$$

Equation 1: Cut-off frequency (f_c), Resistance (R), Capacitance (C)

At low frequencies, ω is small and as $j\omega CR$ tends to zero, the voltage gain is approximately 1. At high frequencies, ω is large and as $j\omega CR$ tends to infinity, the voltage gain is approximately 0. This demonstrates that at higher frequencies, the voltage gain decreases as the low-pass filter removes or blocks higher frequencies above the cut-off.

2) $$\omega = 2\pi f$$ 3) $$\frac{v_o}{v_i} = \frac{1}{1+j\omega CR}$$

Equation 2: Angular frequency (ω), Frequency (f). Equation 3: Voltage output (v_o), Voltage input (v_i), $j^2 = -1$, the imaginary unit, Capacitance (C), Resistance (R)

Most frequencies below the cut-off frequency follow a plateau shape of the bode plot. This implies that the frequencies below the cut-off are allowed to pass through the filter and no/little frequency is removed. Ideally, for a low-pass filter, all frequencies higher than the cut-off frequency should be impassable as demonstrated in the bode plot in Figure 5a and all frequencies before cut-off should not be filtered. However, there is a decrease of -3dB at the cut-off frequency and a -20dB/Decade slope. This gradient of the slope is also known as the 'roll-off rate' and is measured in dB/Decade, which is defined as the rate of gain of power for every factor of ten increase of frequency. There is also a phase shift of -45˚between the output and input signal at the cut-off frequency at an angle of -45˚. The output signal lags behind the input signal due to the time it takes to charge the capacitor.

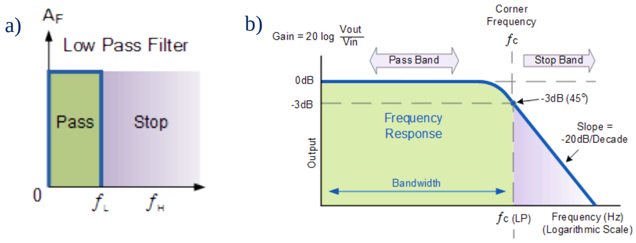


Figure 5: a) Ideal bode plot of low-pass filter, b) Low-pass filter

2.5 Capacitors

Capacitors have applications in radio tuning circuits, MRIs and clocks. A capacitor is an electrical component that can store electrical charge. The effect of a capacitor is capacitance, measured in Farads. An industrial capacitor is constructed with two parallel conductive metal plates, most commonly metals, divided by an insulating material, known as a dielectric. As a voltage is applied over the capacitor, positive charge accumulates on one plate and negative charge on the other. This generates an electric field by which the capacitor can store energy.

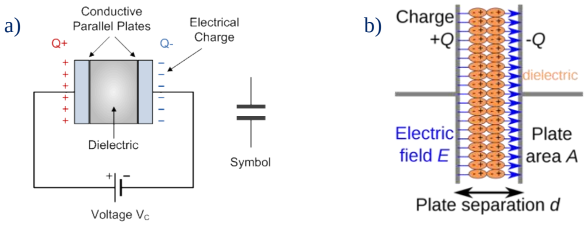


Figure 6: a) Diagram of capacitor connected to a voltage,
b) Polarization of atoms in dielectric material

Most dielectrics are made from insulating materials such as porcelain, glass and plastic. When an external electric field is applied, the dielectric will not allow current to flow through as there are no delocalised electrons in their structure, it undergoes electric polarisation [13]. This occurs when an electric field alters the cloud of negative electrons that surround the positively charged nucleus of an atom. Consequently, this distortion makes one side of the atom slightly negative and the other slightly positive, causing polarisation in the atom. Each atom partially aligns with the electric field; the slightly negative side of one atom attracts the slightly positive side of another atom. The charged boundaries of the dielectric induce an electric field that opposes the external electric field.

3 Materials and Fabrication

3.1 Cold Soldered Low-Pass Filter

In the initial stage of the project, a simple low-pass filter was produced using a 10kΩ resistor and a 100μF capacitor, both were cold soldered using *Bare Conductive* Electric Paint [14] onto regular paper, arranged as a low-pass filter. *Bare Conductive* is a British company producing electronic hardware and kits, and electric paint. The locality of the company is advantageous to 'low-cost' aspect of the project since the delivery of products covers a smaller distance than if it were an international company, and transportation methods could be less damaging to the atmosphere. The net resistance of the whole circuit was measured to be 15kΩ and cut-off frequency was calculated to be 110mHz. The RC circuit was connected to a frequency generator and an oscilloscope to observe and measure the output.

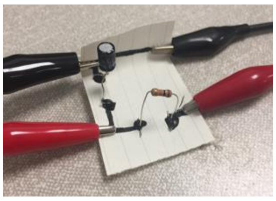


Figure 7: Cold soldered low-pass filter connected to voltage input

Cut-off frequency observed from the oscilloscope was found to be 71.2mHz, which was similar to the theoretical cut-off frequency calculated. The observed cut-off frequency was slightly lower, this is possibly due to the excess of electric paint on the base of the passive components used to secure the wires to the substrate which contribute to a higher net resistance, thus reducing the cut-off frequency. Although paper is widely available, cost-effective and green, the use of this non-conventional material in electronics can be unfavourable down to the rigidity and hydrophilicity of the paper. Regular paper has a weight of 80gsm, which implies that the material is not robust and is quite flexible. In the field of electronics, having a sturdy substrate helps to minimise tensile stress which could affect or even damage the electric components in a circuit. For the experiment, the flexibility of the paper was not beneficial as the circuit deformed when connecting to the voltage supply. Due to the paint being water-based, the paper substrate buckled slightly underneath as the water was absorbed into the material, the same as paint used in art would.

Resistance (net)	**Capacitance**	**Cut-off Frequency (Theoretical)**
15kΩ	100μF	0.11Hz

3.2 Screen Printed Low-Pass Filter Design 1

To be able to print an RC filter, the capacitor must be designed so that it lies flat on the substrate and it should also be simple to assemble. The construction of the capacitor consists of having a bottom electrode that would be printed onto the surface of the substrate. This replicates the first metal plate of a conventional capacitor that would be connected to the resistor in a low-pass filter. The dielectric follows on top, covering the bottom electrode completely and extends slightly beyond the area of the bottom electrode to avoid short circuiting. The top electrode resembling the second metal plate of the capacitor would be printed parallel, displayed in Figure 8a, to the bottom electrode and dielectric, and should encompass the bottom electrode.

The low-pass filter was assembled by screen printing sections of the circuit to form layers. A stencil with permeable regions in the shape of the layers of the components was used to guide the conductive paint and albumen through to the paper, with help from a straight glass blade. The first screen printed layer incorporated the resistor and bottom electrode of the capacitor which was transferred onto regular printing paper. There was less buckling effect on the paper as the layer of electric paint was thinner compared to the cold soldering. Due to the high resistance of the electric paint, the wire was a substitute for the resistor, and had a net resistance of approximately 800Ω. Both the bottom and top electrode of the capacitor had an area of $1cm^3$ (10mm x 10mm). A layer of albumen measuring 1.4mm x 1.4mm was screen printed onto the bottom electrode and left for the water contents to evaporate without treatment (in the form of chemical or thermal treatment). The top electrode was printed directly in line with the bottom electrode with the connective on the paper.

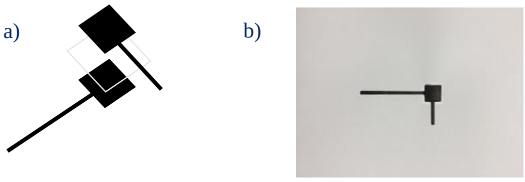


Figure 8: a) Exploded diagram of low-pass filter template, b) Screen printed low-pass filter on paper

Resistance (net)	**Capacitance**	**Cut-off Frequency (Theoretical)**
800Ω	8-10pF	≈22MHz

The frequency generator used to test the circuits had a maximum frequency generation of 20MHz. This was a major limitation for the circuit as the calculated cut-off frequency was ≈22MHz, so the filter was redesigned to have a larger resistance and larger capacitance. A 50mm x 2mm strip of screen printed electric paint had a resistance of 800Ω. To increase the resistance (which in turn would reduce the cut-off frequency) a serpentine pattern was incorporated into the design to minimise the amount of substrate that would be used for the circuit. The resistance of the resistor calculated would be ≈7kΩ. The capacitor was also redesigned to avoid short circuiting and to increase capacitance. The ratio of the area of the bottom electrode to the dielectric to the top electrode would be 4:25:16, showing that the bottom electrode would be smaller than the top electrode. Additional layers of egg white would reduce the risk of short circuiting, although doing this would give a smaller capacitance from the equation in Equation 4.

$$C = \frac{\varepsilon A}{d}$$

Equation 4: Capacitance (C) in Farads, Dielectric Constant (ε), Area of plate overlap (A) in m^2, Distance between plates (d) in m.

3.3 Screen Printed Low-Pass Filter Design 2

To begin the screen printing process, a stencil was prepared by cutting out the design of each layer of the low-pass filter from sheets of A4 cartridge paper. The vertical and horizontal strands of the serpentine resistor were separated into two unconnected templates to minimise movement and bending of the cartridge paper, which would consequentially distort the design and cause the electric paint to spread underneath the impermeable sections of the stencil. The resistor and bottom electrode were printed onto a piece of watercolour card as the base of the circuit using the electric paint which was guided through, and deposited in the gaps of the template using a straight-edged blade. This type of specialist card was pre-stretched, involving the process of stretching the card with water, which alters the permeability of the material, minimising water absorption into the card to prevent buckling of the level surface. Due to the relatively high water contents in both the electric paint and egg white, screen printing onto watercolour card proved much easier since the regular printing paper absorbed the water from both the paint and egg white, causing the surface to bend. This resulted in inconvenience when printing further layers onto the unstable surface as the paint could not be applied evenly and straightforwardly. The unintentional tensile stress would have increased the resistance of the circuit as the length of the paint was increased. Despite showing characteristics of large thickness, strength and low permeability, the watercolour card is more costly than regular paper and requires the additional process of stretching, therefore increasing the cost of the RC filter. Overall, the watercolour card possessed characteristics more suitable for the project.

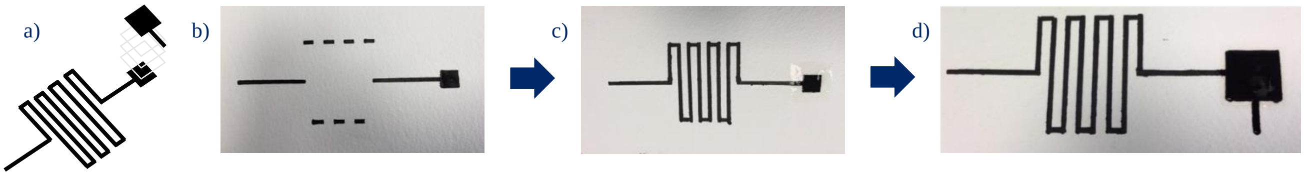


Figure 9: a) Exploded view of low-pass filter stencil design, b) Screen printing in steps of resistor and bottom electrode for easier transfer, c) Resistor, bottom electrode and egg white dielectric layer screen printed, d) Complete screen printed low-pass filter

After leaving the paint to dry completely at room temperature, the egg white was transferred on top of the bottom electrode of the capacitor, implementing the same printing method, and was left to dry at room temperature. A further 2 more layers were screen printed and given the same treatment. The top electrode of the capacitor was screen printed using the electric paint.

Resistance	**Capacitance**	**Cut-off Frequency (Theoretical)**
3.65kΩ	0.35nF	125kHz

3.4 Inkjet-Printed Low-Pass Filter

The inkjet printer used was the *Epson Stylus C88+* [15] model which used micro-piezo technology for prints. From previous runs of the inkjet printer, the main concern was the appearance of gaps within the electrodes, preventing current to flow through, thus creating an incomplete circuit. These gaps were solid lines containing no conductive ink that would run horizontal across the PET. Printing multiple layers onto of the existing ones proved to be ineffective, therefore to avoid this problem, two electrodes were printed separately and were adhered together using the egg white dielectric, therefore, creating a complete circuit.

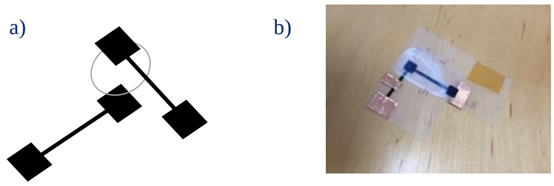


Figure 10: a) Exploded view of low-pass filter inkjet printer design, with egg white drop cast, b) Complete inkjet printed low-pass filter on PET

Carbon black ink used as the conductor contained 9.5% carbon black, a fine carbon powder used in pigments, and the majority was composed of water (85%). The carbon black ink was inkjet-printed onto a PET (polyethylene terephthalate) substrate twice, matching the design in Figure 10a. The *Novacentrix* PET [16] used was chemically treated on the printing side of the film, and helps the ink to be immediately conductive. A small volume of egg white was drop casted onto one electrode of the capacitor and the second electrode was superimposed, with the wire extending perpendicular to first printed wire, and was left to dry at room temperature. However, the egg white had spread and created a large area dielectric between the two sheets of PET, in a tendency known as capillarity [17]. This action occurs due to the stronger attraction between the water molecules in the egg white and the surfaces of the PET film rather than to the other water molecules in the egg white, and causes the liquid to pull and spread across the film in Figure 10b. Having the increased dielectric area would not have a major impact on the capacitance as the capacitance is dependent on the area overlap of the plates, and not the excess area of the dielectric.

Resistance	**Capacitance**	**Cut-off Frequency (Theoretical)**
7.6kΩ	Inconclusive: capacitance overloaded the capacitor meter	Inconclusive

4 Results and Discussion

Thermal Treatment

Additional low-pass filters were fabricated on watercolour card to test whether thermal treatment of the egg white dielectric would give a different capacitance and visual effect. Baking each layer of the dielectric on a hot plate until dried gave a smoother appearance; each layer of egg white had a more even surface with less cracks from the evaporation process, and therefore allowed the top electrode of electric paint to be dried without breaks. The filters that were given thermal treatment looked cleaner and neater than those that had been left to dry at room temperature. A baked filter with screen printed layers: 1x80˚C, 4x70 ˚C, 1x70 ˚C (drop casted) and 1x70 ˚C showed characteristics of a band pass filter - which is made by connecting a low-pass circuit to a high pass circuit [18] and has two cut-off frequencies - and even filtered low frequencies at 10Hz. Both baked filters at 60˚C with three and five layers of egg white showed no filtering effect.

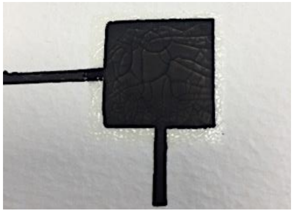


Figure 11: Cracks in screen printed top electrode with egg white dried at room temperature

Screen Printed Low-Pass Filter Design 2 on Card Substrate

The low-pass filter with three layers of egg white left to dry at room temperature had an observed cut-off frequency of ≈170kHz, which is a considered as a low frequency, and has a conventional use in radio navigation aid such as Loran-C [19]. The capacitance was measured to be around 0.35nF using a meter, however, taking the measurement degraded the dielectric, and so the capacitance was decreasing. At extremely low frequencies, the input voltage should have been the same as the output voltage as cut-off frequency of the low pass filter had not yet been reached. The input voltage was 2.00V peak-peak, however, the output voltage at a frequency of 1Hz was observed to be 1.65V peak-peak. This signifies that there was a power loss at some point in the circuit. There was an approximate roll-off rate of -20.5dB/decade after the cut-off frequency, having a value almost identical to the -20dB/decade theoretical roll-off rate, and roughly a -3dB roll-off at the cut-off frequency displayed in Figure 12a. This screen-printed low-pass filter on watercolour card demonstrated characteristics very similar to those of a conventional low-pass filter.

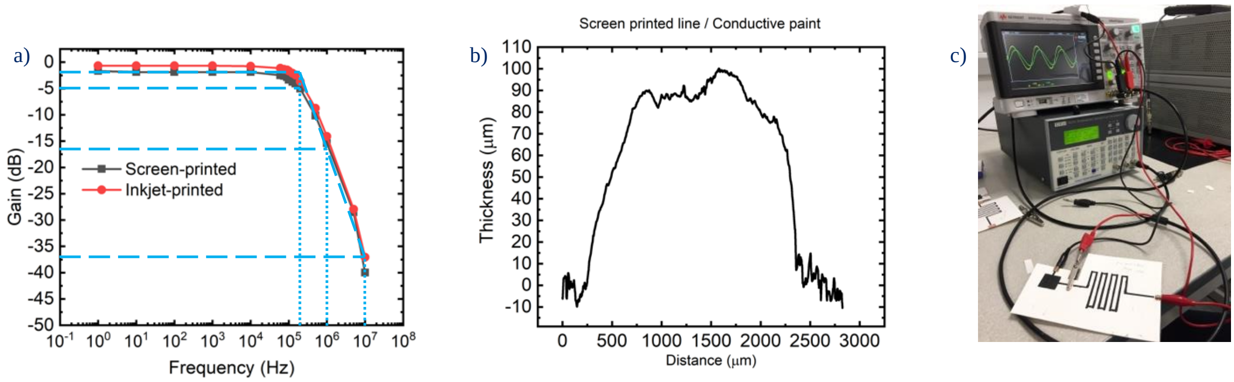


Figure 12: a) Bode plot of low-pass filter, focussing on the screen printed line, b) Thickness measurement of screen printed line of resistor, c) Screen-printed low-pass filter connected to voltage input. Yellow signal: Voltage input, Green signal: voltage output

Through conducting a thickness examination of one of the screen-printed lines in the resistor, it was found that the layer had an average thickness of around 90μm, equal to 0.009cm depicted in Figure 12b. The approximate width of each screen-printed line of the resistor was 0.21cm, which gave an estimated cross-sectional area of $1.89\text{x}10^{-3}\text{cm}^2$ (assuming that the cross-section is a rectangle). The resistance of the resistor was previously measured to be 3.65kΩ and the resistor had a total length of ≈45.8cm. By acquiring these measurements, the resistivity of the electric paint could be calculated using the equation in Equation 5, and was calculated to be 0.15Ωcm. A conventional copper wire has a resistivity of around 1.72μΩcm, and therefore demonstrates that the electric paint can act as an effective resistor due to its high resistivity.

$$\rho = R\frac{A}{l}$$

Equation 5: Resistivity (ρ), Resistance (R) in Ohms, Cross-sectional area (A), Length

A functioning capacitor was made with the egg white, although the insulator had not been very effective so far, and was degrading over time. The electric paint had bled into the egg white whilst drying, and spread more at room temperature than when the dielectric layers were baked. This could have changed the dielectric or insulating capabilities of the egg white. Perhaps the layering of the egg white dielectric could have affected the insulating effect of the egg white.

Inkjet Printed Low-Pass Filter on PET

The low-pass filter was ink-jetted onto glossy paper using carbon black ink, but had no filtering effect perhaps due to the ink being absorbed into the paper fibres rather than remaining on the surface. An ink-jetted low-pass filter on a PET substrate with drop casted egg white without thermal treatment had an observed cut-off frequency of around 200kHz. As seen from Figure 12a, although there is still a voltage loss at very low frequencies, has an approximate output voltage of 1.85V peak-peak at 1Hz. This voltage output was higher than that of the screen-printed low-pass filter at 1Hz, showing a smaller loss of power that could have been due to the smaller scale of the circuit of filter on PET, presenting less possibility of power loss. Similar to the screen-printed filter, the inkjet-printed filter follows a near-identical roll-off rate and a -3.5dB drop at the cut-off frequency. This also exhibits characteristics of a conventional low-pass filter, whilst having a smaller power loss compared to the screen-printed filter. The thickness of a droplet of ink-jetted carbon black, as displayed in Figure 13, was measured an average of 1.3µm. This thickness was a lot thinner than the screen-printed line, giving a smaller cross-sectional area and therefore increased the resistance of the carbon black line. This carries an advantage over screen printing as the carbon black resistor had a smaller length than the electric paint resistor, but had a higher resistance, meaning that less ink needs to be used for the resistor. Though, the use of inkjet printing and PET as the substrate increase the cost of the fabrication process and is less environmentally friendly.

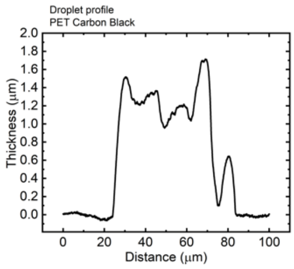


Figure 13: Thickness measurement of Carbon black droplet on PET

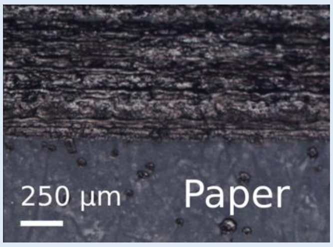
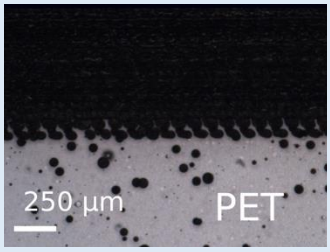
There are many advantages to using screen printing over inkjet printing such as the cost and environmental factors. However, inkjet printing is a quicker and more accurate method. Overall, the screen printing process is more beneficial for the project as it keeps to the low-cost and 'green' aim and can be done on card, which is a preferred substrate over PET due to the environmental issues with polyesters.

5 Conclusion

Through successfully screen printing carbon-based electric paint and egg white onto a watercolour card substrate, a low-cost low-pass filter has been fabricated using inexpensive and green materials used in daily life, while using a cost-effective and simple printing process. This filter was assembled without the use of machinery, proving to be a vital advantage as it demonstrates that with the suitable materials, RC filters and perhaps other electronics can be produced at home rather than in electronic labs. This low-pass filter can attenuate frequencies above a 170kHz cut-off frequency and possesses characteristics of a conventional low-pass filter. The use of greener materials can make electronics more sustainable and could also be a progression towards recyclable electronics. Reducing the use of non-renewable resources means that there will be a smaller demand for the extraction of more expensive elements which generates pollution. Alternatively, a carbon black inkjet-printed low-pass filter was made on a PET substrate with egg white, and can filter frequencies above 200kHz. This filter was time effective and can be done easily at home with an ordinary inkjet printer and PET film at an affordable cost. Improvements to the project can be made by accurately drop casting the egg white onto the inkjet-printed filter, avoiding too much spread. Instead, developments into ink-jetting egg white can be made by changing its velocity, this will help the project be more consistent with the techniques used. Finding a printable greener ink and substrate would help to reduce costs and environmental disadvantages of the inkjet-printed filter. The aim to make a capacitor using egg white was accomplished, although developments can be made to the egg white and circuit to improve its insulating capabilities. The project can be advanced by being able to tune the filter with control to other frequencies. Both low-pass filters produced are progressions towards low-costing electronics using materials from daily life.

Comparative Table Between Screen Printing and Inkjet Printing

Aspects	Screen Printing	Inkjet Printing
Speed/Time	Screen printing process was relatively slow as time was required for each layer to dry, however, pushing the paint or egg white through the stencil was done quickly to prevent excessive bleeds underneath the stencil. A long duration of time was used to hand-cut the stencils for the screen prints as the resistor design was slightly intricate.	Creating design template of the electrodes on the computer took a relatively short time. The ink jet print was very quick and efficient and the ink dried immediately due to the small size of each droplet and water content.
Cost	Materials used in the screen prints were cartridge paper, watercolour card and a glass blade. These materials were quite cheap and are widely available, and helped the project adhere to the 'low-cost' aim.	Model used was the Epson Stylus® C88+ inkjet printer costing £80, a little more expensive than simple models. However, a cheaper inkjet printer can be used likewise.
Environmental concerns	Stencil used was cartridge paper and substrate was watercolour card. Both materials are biodegradable and can be recycled. However, the production of paper and card require trees and deforestation so is damaging to the environment if the production is not sustainable.	The Epson inkjet printer was powered by an external power source, so electricity was used which is generated from fossil fuels, a non-renewable source of energy. The substrate used was PET, a form of polyester that does not biodegrade but instead photodegrades. This means that PET fragments over time and can absorb toxins and release them as toxic emissions.
Ink	Electric paint used was safe on skin and could be washed using soap and water. The paint could be stored at room temperature and did not emit toxic fumes when being applied and drying. The viscosity of the paint was high which contributed to an easier transfer through the stencil.	The ink used contained 9.5% carbon black and was mainly water-based. The contents of the ink were not very hazardous, were safe to use and did not bleed in a water test.

Printing accuracy/Quality	The stencil was cut sharply and the outlines were accurate. However, the transfer of paint through the stencil was rather messy, and a lot of paint was wasted. The paint spread underneath the stencil in a few areas, especially the resistor. Due to the high viscosity of the egg white, measured to be 23cP, or 23 times more viscous than water, and how the egg white molecules hold together, screen printing was difficult and bubbles of air formed in the dielectric. The centre of the dielectric was thicker than the edges as the egg white was pulled to the centre as the stencil was removed.  Figure 15: Magnified image of screen-printed electric paint The dried electric paint, although seeming to have a smooth surface through the naked eye, had very small fissures throughout the screen-printed lines.	Inkjet printing involves forcing droplets at micro-scale to reach the substrate. Due to the small size and speed of each droplet, the print was very sharp and neat.  Figure 14: Magnified image of ink-jetted carbon black droplets Displayed in Figure 14, each droplet was ≈50µm in diameter and packed closely together, giving a very solid graphic. Each droplet seemed equidistant and formed a scale-like layer.

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7 Bibliography

[1] V. Subramanian, J.B. Chang, A. de la Fuente Vornbrock, D.C. Huang, L. Jagannathan, F. Liao, B. Mattis, S. Molesa, D.R. Redinger, D. Soltman, S.K. Voltman and Q. Zhang, "*Printed electronics for low-cost electronic systems: Technology status and application development*," IEEE. 4681691, 2008.

[2] Y. Wang, Y. Qiu, S.K. Ameri, H. Jang, Z. Dai, Y. Huang and N. Lu, "*Low-cost, µm-thick, tape-free electronic tattoo sensors with minimized motion and sweat artifacts*," npj. Article number. 6, 2397-4621, 2018.

[3] J.W Chang, C.G Wang, C.H Huang, T.D Tsai, T.F Guo, T.C Wen, "*Chicken Albumen Dielectrics in Organic Field-Effect Transistors*," Adv. Mater. 23(35), p. 4077-4081, 2011.

[4] A.N. Sokolov, M.E. Roberts, Z. Bao, "*Fabrication of low-cost electronic biosensors*," Mater. Today, Vol. 12, Iss. 9, 2009.
[5] Y. Han, J. Dong, "*Electrohydrodynamic (EHD) Printing of Molten Metal Ink for Flexible and Stretchable Conductor with Self-Healing Capability*," Adv. Mater. Tech., Vol. 3, Iss. 3, 1700268, 2017.
[6] N. Storey, "*Electronics A Systems Approach*," 5th ed. Harlow: Pearson, 2013.
[7] Wolfram Research, Inc., (2007), *ElementData* [Online]. Available: https://reference.wolfram.com/language/ref/ElementData.html
[8] J. Clark, (2000), *Giant Covalent Structures* [Online]. Available: https://www.chemguide.co.uk/atoms/structures/giantcov.html
[9] C. Woodford, (2009/2017), *Piezoelectricity* [Online]. Available: https://www.explainthatstuff.com/piezoelectricity.html
[10] EPSON®, *Micro Piezo Technology* [Online]. Available: https://www.epson.co.uk/innovative-technologies/micro-piezo-technology
[11] V. Ryan, (2002/2018), *Screen Printing* [Online]. Available: http://www.technologystudent.com/designpro/prtpro4.htm
[12] Electronics Tutorials, *Passive Low Pass Filter* [Online]. Available: https://www.electronics-tutorials.ws/filter/filter_2.html
[13] Encyclopaedia Britannica, G. Young, (1998/2017), *Electric Polarization* [Online]. Available: https://www.britannica.com/science/electric-polarization
[14] Bare Conductive, *Electric Paint.* Available: https://www.bareconductive.com/shop/electric-paint-10ml/
[15] EPSON, *Epson Stylus C88+ Inkjet Printer.* Available: https://epson.com/For-Home/Printers/Inkjet/Epson-Stylus-C88%2B-Inkjet-Printer/p/C11C617121
[16] Novacentrix, *Novele^{TM} Pack*. Available: https://www.novacentrix.com
[17] Exploring Our Fluid Earth, *Hydrogen Bonds Make Water Sticky* [Online]. Available: https://manoa.hawaii.edu/exploringourfluidearth/chemical/properties-water/hydrogen-bonds-make-water-sticky
[18] Electronics Tutorials, *Passive Band Pass Filter* [Online]. Available: https://www.electronics-tutorials.ws/filter/filter_4.html
[19] ESA, (2013), *Satellite Frequency Bands* [Online]. Available: https://www.esa.int/spaceinimages/Images/2013/11/Satellite_frequency_bands